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MAGMATIC DIFFERENTIATION IN MOUNT GIRNAR

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ABSTRACT

The Girnar laccolith was intruded into a thick covering of basalt of late Cretaceous or early Eocene age in Kathiawar, India, which was lifted up in the form of a dome. Slow cooling of the magma gave rise to olivine-gabbro, diorite, monzonite, syenite, nepheline-syenite, and granophyre. This paper deals principally with the mechanism of intrusion and differentiation. Three phases of movement are represented by olivine-gabbro, diorite-monzonite, and granophyre, respectively. Diorite and monzonite occur in the center and are surrounded by olivine-gabbro. Granophyre is intruded in the marginal hills of basalt in the form of large dikes. This structural feature is explained by a circular system of fractures in basalt due to arching. The differentiation is shown to be the result of fractional crystallization; sediment-assimilation or immiscibility in the liquid state is regarded as improbable. The physical conditions which prevailed indicate quiet crystallization and absence of convection currents and crystal settling. Field evidence has been noticed supporting the origin of nephelite-syenite by the dissociation of the polysilicate feldspar.

INTRODUCTION

The Girnar Hills form an imposing and characteristic land mass in the plains of Kathiawar. Considerable importance attaches to them from a religious and archaeological point of view, and the shrines on the top of the hill are visited by a large number of pilgrims every year. Geologically they are no less important, yet so far little information exists about the interesting varieties of rocks they contain, or the structure of the hill ranges. They were first

noticed by Fedden[1] during the Geological Survey of Kathiawar, and have been described as being formed of the dioritic core of an ancient volcano which was presumably a center of eruption for the lava flows which cover the country. The quaquaversal dip in the surrounding basalt and the topographic features are possibly suggestive of a volcano, but there is little doubt that the rocks constitute a plutonic intrusion in the form of a laccolith, with a large number of differentiated types, which is probably unique in being the first of its kind studied in India. Thanks of the authors are due to Dr. J. W. Evans, who first recognized the importance of these hills[2] and at whose suggestion this work was taken in hand. A petrographical investigation of a collection of rocks made by him thirty years ago has been carried out at the Royal School of Mines, London, by Dr. M. S. Krishnan, but the results are not yet published and have not been available to the authors. It is proposed in this paper to indicate in brief the leading petrographical features of the rock types and to describe in detail their distribution and structural relationships particularly with a view to studying the mechanism which gave rise to the large number of igneous rocks within this small area. A summary of the geology of the peninsula is compiled below for the sake of reference to the stratigraphical relationships of these rocks.

GEOLOGY OF KATHIAWAR

The province of Kathiawar forms a peninsula on the west coast of India. The country is for the most part plain and is covered with extensive lava flows known as the Deccan Trap. The oldest rocks met with in Kathiawar are uppermost Jurassic in age; a short account of these and the succeeding formations is given below.

JURASSIC ROCKS

The oldest formation belongs to the Umia horizon in Indian stratigraphy, which is regarded as uppermost Jurassic to lower Cretaceous in age. It is composed of soft white ferruginous sandstone and shale with pebble beds from which some fossil plants have been

[1] *Memoir* (Geological Survey of India), Vol. XXI, 1884.

[2] J. W. Evans, "A Monchiquite from Mount Girnar," *Quart. Jour. Geol. Soc.*, Vol. LVII, No. 225.

obtained. This group of rocks outcrops in the northeast of Kathiawar and forms a large patch round Dhrangadhra, a native state of this province.

CRETACEOUS ROCKS

a) *The Wadhwan sandstone group.*—The foregoing group is directly overlaid by a series of strata composed of ferruginous sandstones and occasional argillaceous deposits capped by thin cherty calcareous bands. These beds correspond to the Bagh beds and the infra-trappean rocks of Peninsular India and therefore belong to the Cenomanian age of European Cretaceous. They principally outcrop in the north near Wadhwan, from which the name of the group is derived.

b) *The trappean grits.*—Overlying the Wadhwan sandstones and underlying the trappean rocks occurs a series of grits occupying a very negligible area. These rocks present an appearance of decomposed trap but are gritty due to the presence of quartz grains.

c) *The trap rocks.*—The greater part of the province of Kathiawar is covered by lavas of the Deccan Trap. These basaltic lava flows were the result of a great outburst of volcanic energy which led to the eruption of a thick series of lava from fissures and cracks in the surface of the earth. The mean thickness of the bedded basaltic lavas for the entire province has been estimated to be about 1,800 feet. Petrologically the rock is almost uniform, the most common specimen being a normal augite-basalt of mean specific gravity 2.82. The only variation is in the color and texture of the rock. Plutonic and hypabyssal intrusions connected with the volcanic activity are abundant in the province. Girnar represents the largest of these intrusions; some of the others will be noticed later. The trappean rocks of Kathiawar are the western extension of the Deccan Trap of Peninsular India, which is believed to have been poured out in the interval between the Middle Cretaceous and Lower Eocene.

d) *The inter-trappean beds.*—Certain sedimentary formations are found interstratified with the bedded lavas. They occur at places to the north of Kathiawar toward the base of the volcanic flows. These rocks are generally composed of cherty, porcellaneous shale and limestone from which some organic remains have been obtained.

THE TERTIARY ROCKS

The Tertiary rocks are generally found fringing the coast line to the east and west of the province. They are represented by the Gaj series and the Dwarka beds. The Gaj group consists of yellow limonitic limestones and marls with abundant fossil remains and is succeeded by the Dwarka beds, which consist of soft, gypsiferous clays overlaid by soft, sandy, and argillaceous limestones containing many foraminiferal remains. The Gaj beds are Lower Miocene, the Dwarka bed being younger, probably Upper Miocene in age.

Post-Tertiary deposits are found scattered throughout but mostly occur near the coast line of the province. The most important formation is the famous limestone to which the name Miliolite has been given. It is a fine-grained oölitic freestone largely composed of Foraminifera not infrequently mixed with a large quantity of sand. The town of Junagadh one mile to the west of Girnar is situated on this rock; the basement bed here consists of a bowlder bed and rests on the Deccan Trap.

TOPOGRAPHIC FEATURES AND GEOGRAPHICAL DISTRIBUTION OF ROCK TYPES

The Girnar Hills are situated in the southern part of the peninsula east of the town of Junagadh, 40 miles to the north of the seacoast. It is the largest of a number of intrusions which lie on an east-west line roughly parallel to the coast. The Barda and Alech Hills situated to the west in the Navanagar State are wholly made of granophyre. About 14 miles to the west of Girnar the Osham Hill is also composed of felsitic rock. These are probably all in the nature of laccoliths. They have been studied petrographically to a certain extent[1] but little is known about the forms and structural relations of these masses. They are, however, all intrusions of plutonic and hypabyssal rocks in the basaltic plateau, with occasional acid lava flows, and stand out as prominent landmarks in the flat plains of Kathiawar.

A description of the principal rocks present in Girnar will be given later. It will be sufficient here to enumerate the types in

[1] E. Howard Adye, *Memoir on the Economic Geology of Navanagar State. Reports on the Economic Geology of the Porbundar State.*

order that their geographical distributions may be clearly understood. The intrusive rocks consist of (1) olivine-gabbro, including biotite-olivine-gabbro; (2) biotite-diorite and monzonite; (3) nephelite-syenite, veins of feldspar, and dikes of quartz-feldspar rock; and (4) granophyre and quartz-felsite.

In addition to these may be mentioned basalts and lamprophyres, the latter including some metamorphosed forms of basalt and other rocks which may represent mafic segregations from the magma.

The elevated region in Girnar has roughly a circular or subquadrangular outline with a radius of 9 miles, covering a total area of 67 square miles. A line of high peaks runs east and west on the central mountain, which presents steep scarps on all sides and sends out gigantic radial spurs to the outer circular ranges of hills. The names of important hill ranges with their high peaks are shown on the geological map accompanying this article (Fig. 1). The area can be divided geographically into four parts: (1) the circular outer ranges of hills; (2) the central mountain; (3) radial ridges joining the central mountain to the outer hills; and (4) low plains occupying the intervening area.

1. *The circular range of hills* is, as a rule, deeply escarped on the inside with gentler outer slopes which are dissected into numerous large and small ravines. The continuity of the range is broken by four gorges which form the only outlets to the drainage of the inclosed area. These gorges are situated to the west, north, east, and southeast, respectively. They are dry for the greater part of the year, except during the rainy season, when the western and southeastern gorges support short-lived but torrential streams. The average height of these hills ranges between 1,500 and 2,000 feet, except a few high peaks, of which Datar Pir attains the height of 2,779 feet and overlooks a broad plateau to the southwest.

These hills are composed of basalt with a core of granophyre which occurs in the form of large intrusive dikes. The basalt shows, in general, a quaquaversal dip. It has been considerably fractured by the granophyre at the time of intrusion, and the phenomenon is best seen in Chorpani, the northern half of the northwestern hill range. Abundant sharp, angular xenoliths of basalt in granophyre

can be seen at the junction, and they show as a rule no evidence of fusion or metamorphism. This absence of metamorphic effect is also true of basalt at the junction of the granophyre dike.

FIG. 1.—Geological map of Girnar. References: (1) Gomukhi Kund; (2) Amba Devi; (3) Mali Parab Kund; (4) Gorakhnath; (5) Dattatreya; (6) Kalika Tonk; (7) Hathi Pagla Kund; (8) Bhairo Jap; (9) Sesawan; (10) Hanuman Dhara; (11) Kamandal Kund; (12) Dharmsala; (13) Bhaveshwar; (14) Damodar Kund; (15) Lachhman Tekri; (16) Toda; (17) Vageswari; (18) Ashapir Well; (19) Sakri Ambli; (20) Malbela; (21) Suraj Kund; (22) Sarkharia; (23) Jina Bawa Ki Madhi; (24) blocks of conglomerate referred to in the paper.

The granophyre attains its maximum development in the south, forming the high peaks of Gadhekot and Kunchia hills. It forms the backbone of Joginia and Choripani hill ranges to the northwest. In the northeastern and eastern parts, the outcrop is considerably diminished, but its continuity underground can be traced by the presence of veins too small to be shown on the map. The occurrence of granophyre in Girnar is thus restricted to the outer hills, in which it forms a circle around the basic rocks of the central area.

Here may be mentioned the occurrence of a small patch of conglomerate on Khorial Ridge above the newly constructed dam across the broad valley west of Datar Pir. Large blocks occur sandwiched between granophyre and basalt. The largest pebbles are between 1 and 2 inches in diameter, and with diminution in the size of the pebbles, the rock approximates to a grit. Bedding is clearly visible in the broken blocks. They have evidently been brought up from some depth by the granophyre at the time of intrusion and may indicate the presence of trappean grits under the basalt.

2. *The central mountain.*—This consists of a broad ridge with a linear extension east and west marked by the high peaks of Amba Devi, Gorakhnath, Dattatreya (3,666 ft.), Anusuya, Kalika Tonk (3,295 ft.), and Ghurmukha. It is composed of monzonite and diorite, with minor intrusions of nephelite-syenite and basaltic dikes. Monzonite is typically developed at Maliparab Kund, and there is a gradual variation eastward to diorite and biotite-diorite at Dattatreya and Kalika Tonk, respectively. The relations of this mass to the surrounding olivine-gabbro are somewhat variable. To the east and north of Ghurmukha it appears to be intrusive into biotite-olivine-gabbro. The latter rock, rich in biotite, is invariably present at the junction and represents a phase of the olivine-gabbro which is restricted to the periphery of the central mountain.

3. *Radial ridges.*—The central mass is connected with the outer hills by four radial ridges which have an average height of 1,000–1,500 feet. They are principally composed of olivine-gabbro except near the junction with the central mountain, where an unusual amount of biotite is developed as indicated above. The greatest development of gabbro occurs at Lhasa Pawan, which is a continuation of the central line of peaks to the southeast beyond Ghurmukha. Here it attains a height of about 2,000 feet and the rock is conspic-

uously banded on the weathered surfaces, giving the appearance of a dip to the west.

Intrusions of nephelite-syenite and quartz-feldspar rock occur at many places on these ridges, and well-formed crystals of quartz can often be picked up from the latter dikes traversing gabbro, particularly on the footpath from the Ashapir well to Bordevi where it crosses Chorghori. Large pieces of magnetite and crystals of augite are found scattered on Koribara and other outcrops of olivine-gabbro to the north.

4. *Plains.*—Low plains inclosed between the outer hills and the central mountain and separated from one another by the radial ridges divide the forest of Girnar into four quadrangles. The plains to the west and north are more or less flat with a shallow covering of alluvium. To the south, the Boria forest presents an uneven surface, and the low country to the east consists of a broad valley draining out through the eastern gorge. Ignoring the alluvium, the plains are geologically shared by the basalt on the outer side and gabbro on the inner margin.

ROCK TYPES

OLIVINE-GABBRO

This is a coarse-grained rock with large equidimensional crystals of augite and brown specks of hematite associated with olivine set up in a white matrix of feldspar. The characteristic appearance of olivine-gabbro, due to weathering, is very prominent in the field. The crystals of pyroxene stand out in relief, due to their slightly higher power of resistance to weathering, and the crystals of olivine, decomposed partially or completely into hematite, give the rock a pitted appearance. The rock is generally massive in structure; its banded appearance at Lhasa Pawan and some other localities has already been referred to. This is undoubtedly due to a banded arrangement of the minerals, the more easily weathered crystals of olivine alternating with the more resisting bands rich in augite, although this is not very clear in hand specimens or in microscopic sections.

A typical specimen of this rock shows under the miscroscope a holocrystalline, granitoid aggregate of plagioclase, olivine, augite,

and a small amount of biotite. The feldspar, which is mostly labradorite, was the first mineral to crystallize because not only does it show ophitic relationship with augite, but olivine also incloses small plates of the feldspar. A specimen from the central pass on Koribara consists of plagioclase, a fair quantity of simple-twinned orthoclase, augite, and small quantities of hypersthene, olivine, and biotite. This rock approximates to olivine-monzonite.

The variable components in the mineral composition are biotite, hypersthene, and orthoclase. Biotite becomes an important constituent in the neighborhood of the central dioritic mass, where hypersthene is also often present. Orthoclase is seen in a specimen from the locality mentioned above and also in a gabbro vein in the Addo Ridge northeast of Nes. In these olivine is present in traces, or is absent. Segregations of magnetite and large crystals of augite often 1 inch in diameter are found at various places, particularly to the north and northwest; a specimen of magnetite about 4 inches in diameter was picked up showing distinct polarity. It will be noticed that the gabbro with the segregation of heavy minerals occurs on the border of the main intrusion, and there was no tendency for these to sink by gravity toward the bottom.

DIORITE AND MONZONITE

The principal minerals of these rocks are plagioclase, orthoclase, hornblende, a green augite, and biotite, with apatite, zircon, and sphene as accessory minerals. The relative quantities of these are very variable as we travel from Maliparab Kund on the west to the central peaks. At the former locality hornblende is absent, biotite and green augite form the colored minerals, and the two feldspars, andesine and orthoclase, are present in nearly equal quantities. The accessory minerals are conspicuously developed. The rock is thus a typical monzonite. In the central peaks of Amba Devi and Gorakhnath an increase takes place in the amount of hornblende, both biotite and pyroxene decrease, and the calcic feldspar becomes predominant. At Dattatreya the rock is a typical diorite with hornblende and feldspar. Farther to the east the amount of biotite again increases and some augite is present. Near Kalika Tonk there is a tendency for the rock to become heterogeneous; the mica and

the feldspar often separate into parallel bands. Large blocks of uniform diorite are often riddled with an intricate system of veins of femic and feldspathic minerals, respectively, indicating local segregation in the fluid residue during the last stage of solidification. Much of the feldspar in these occurrences is kaolinized.

NEPHELITE-SYENITE AND SYENITE

Nephelite-syenite is generally cream colored, spotted black and pinkish red with pyroxene and nephelite, respectively. The weathering of this rock is very characteristic; the exposed surfaces invariably show reticulated and elongated cavities due to the removal of nephelite by solution. An acquaintance with this feature greatly helps in distinguishing the rock in the field. It consists of a granitoid aggregate of alkali feldspars, nephelite, sodalite, cancrinite, and aegirite. The feldspar is mostly kaolinized. The rock is intrusive into diorite, olivine-gabbro, and basalt. Outcrops of nephelite-syenite have not been shown on the accompanying geological map owing to their irregular and wide distribution. It may, however, be noted that they are abundant in the central Girnar, especially on its western and southern lower slopes. Notable localities where the rock may be examined are (1) Dharmsala at the bottom of the stairs leading up to the top of Girnar, (2) Chorghori Ridge, and (3) the low ridge between Ghurmukha and Lhasa Pawan.

GRANOPHYRE AND QUARTZ-FELSITE

This rock varies from pale gray to pink in color. The granophyre shows a micrographic intergrowth of quartz and feldspar. These minerals also occur as phenocrysts in a groundmass of quartz and feldspar. Some biotite, magnetite, hematite, and a little zircon form the accessory minerals. Both the orthoclase and plagioclase feldspars are present. Marginally, granophyre changes to a grayish-blue rock which, under the microscope, shows a spherulitic texture. Idiomorphic crystals of quartz form nuclei of radiating fibrous feldspar. This texture is presumably the effect of quicker cooling on the margin of the granophyre dike. The extreme compactness of granophyre has imparted to it great power of resistance to weathering. The well-known inscription of Asoka, inscribed on the

outcrop of this rock in the western gorge, is well preserved after an exposure of over two thousand years.

LAMPROPHYRES

A black rock resembling basalt in its external characters is found near its margin in close association with nephelite-syenite. Dikes of similar rocks appear at a few places in the diorite alone or with similar syenitic intrusions, xenoliths of the black rock occurring in the feldspathic veins. A few specimens, mostly from thin dikes, are very fine grained, others show minute elongated crystals of hornblende set in a feldspathic groundmass with occasional phenocrysts of the latter. A circular isotropic mineral showing anomalous double-refraction is often present and is probably analcite. Well-formed crystals of cancrinite and another colorless mineral with strong double-refraction may be seen. Presence of magnetite and apatite and a green pyroxene as accessory minerals may be mentioned. Some specimens show phenocrysts of augite altering on the margin to hornblende. The monchiquite described by Dr. Evans belongs to this group, and the probable mode of origin of these will be discussed later.

BASALT

This is, as a rule, a dark compact rock with phenocrysts of lath-shaped feldspar. At Mathura in the eastern part of the outer hills an exceptional development of these laths more than an inch in length was noticed in a few large blocks scattered in the valley. At Hajam Chaura the rock is gray in color with an amygdaloidal texture, the amygdules being filled with yellow-green epidote. The rock is highly altered with the formation of secondary chlorite. The unaltered rock consists of olivine, augite, and plagioclase feldspar with magnetite and flakes of biotite.

SHAPE OF THE INTRUSION

The Girnar intrusion forms a roughly circular dome-shaped mass (see Fig. 2, secs. 1 and 2), the base of which is not exposed to view. It is clear from the distribution of rocks given above that the main intrusion occupies the central mountain, the radial ridges, and portions of the plains, and the dikes of granophyre represent associated

intrusions round the base of the main mass. The form of the dome is not symmetrical. It is elongated along the line of high peaks which runs east and west, and there appears to be a greater accumulation of the mass to the south of this line than to the north. This may indicate that the conduit through which the magma came up was in the form of a fissure heading to the north. This corresponds to the greater development of the granophyre in the southern hills as compared to its poor outcrop in the north. Further irregularities in the shape of the dome are seen in the extension of the mass along the radial ridges, where the junction with basalt is high up on the ridge, descending into the plains on either side.

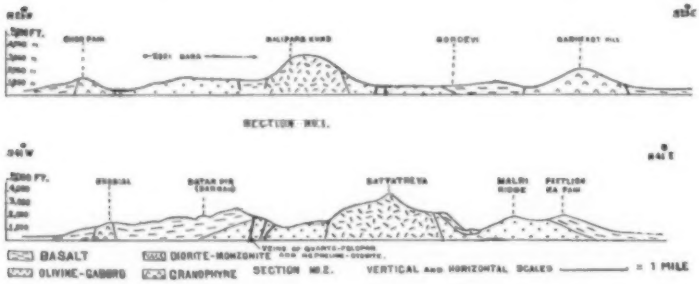

FIG. 2.—Geological sections Nos. 1 and 2

The association of the circular intrusion of granophyre in the form of large dikes is easily explained by reference to the system of fractures which would be produced by the arching up of the basalt. It has been suggested by Palmer[1] that the cracking of the roof into blocks would give rise to wedge-shaped openings which would gape upward on the top and downward around the base. The size of these openings would depend on the degree of curvature in the arching of the overlying basalt round the base, and if the intrusion should result in an unsymmetrical uplifting of the roof, fractures would not be equally developed in all directions; the steeper slopes would suffer greater fracturing than others with a gentle slope. The thinness or absence of dikes in the northern ridges would thus correspond to a

[1] H. S. Palmer, "Structure of the South Moccasin Laccolith, Fergus County, Montana," *Amer. Jour. Sci.*, Vol. X, No. 46, 1925.

gentler slope of contact of the laccolith with the overlying basalt, which was compensated by larger fractures in the opposite direction. The radial ridges probably indicate the relief of stress by radial fractures in the roof of the dome which were filled by the magma.

MECHANISM OF DIFFERENTIATION

From the description of the rock types and their close relationship in the field (p. 290), it is clear that this unique assemblage can only be regarded as one petrological unit derived from a common magma. It may, however, be mentioned that the felsitic intrusions of the Osham Hill and the Barda and Alech Hills do not show a corresponding basic phase of differentiation. The possibility of an initial separation of the magma into two immiscible fluids will be considered later. At Girnar it is probable that differentiation took place *in situ*, and the results of this process are clearly exposed in the field. It is therefore interesting to see how far it is possible to get an idea of the mechanism of separation which gave rise to extreme rock types like olivine-gabbro, granophyre, and nephelite-syenite, together with other rocks of intermediate composition. Apart from the comprehensive theory of differentiation by crystallization advanced by Bowen, the assimilation of sediments by the molten magma has been regarded as a potent factor in the formation of diverse rock types, and it is well to study the possibilities of the sediment-syntectic hypothesis in Girnar. The only sedimentary rock detected consists of a small patch of conglomerate which has already been described. It is marked on the accompanying map (Fig. 1). The sediments below the trap are mostly siliceous and argillaceous; no calcareous rocks are known in the vicinity except the miliolite limestone of Junagdah, which is only a superficial calcareous formation of comparatively recent date.

According to the assimilation theory, the granophyre may be imagined to have been formed by the absorption by the magma of siliceous matter from the conglomerate which may be present on an extensive scale below the basalt. Several considerations, however, militate against this point of view. The junction of the granophyre and the conglomerate has given rise to a heterogeneous rock in which the pebbles or the grit are imbedded in a matrix of granophyre

which regains its normal appearance within a short distance from the junction. Further, the xenoliths of basalt which are abundant in the granophyre have invariably retained their sharp, angular outline, and no mineral change is visible in the veins of granophyre in the basalt. All this shows that this magma was incapable of any solvent action on solid rock, at least in the condition in which it was intruded. The presence of volatiles is also rendered doubtful by the fact that there is no metamorphic action on the basalt except occasional traces of fusion at the points of contact. It is therefore unlikely that the granophyre has been formed by a process of assimilation of sediments. The occurrences of olivine-gabbro, diorite, and monzonite are still more difficult to understand on this hypothesis.

The syntectic hypothesis has particularly been applied to the origin of alkaline rocks. It has already been noted above that no basic sediments are known to occur in the neighborhood. There is, however, ample support from field observations in this area for the alternative point of view put forward by Bowen,[1] according to which in later stages of crystallization the polysilicate molecule $NaAlSi_3O_8$ in the presence of volatiles breaks down into the orthosilicate molecule $NaAlSiO_4$ and quartz. The removal of the fluid rich in volatiles from crystallized quartz to regions of lower pressure may give rise on consolidation to veins of nephelite-syenite. Field observations on the occurrence of this rock in Girnar show that it occurs intrusive in gabbro, diorite, monzonite, and the overlying basalt, clearly indicating for it the latest stage of crystallization. The extreme fluidity of this magma is shown by the intricate system of veins to which it has given rise during intrusion. Its richness in volatiles, which was the cause of fluidity, is evidenced by the metamorphism of the basalt, which will be referred to below. At several localities, especially at Chorghori, it was observed that the veins of nephelite-syenite were accompanied by veins of a quartz-feldspar rock, although no vein could be traced in which one rock merged into the other. Veins of soda-feldspar corresponding to oligoclase also occur under similar conditions. This indicates that these rocks bear a genetic relationship, and goes to support Bowen's hypothesis of the origin of alkaline rocks.

[1] N. L. Bowen, "The Later Stages of the Evolution of the Igneous Rocks," *Jour. Geol.*, Vol. XXIII, 1915. Supplement.

An important objection raised against this point of view is the absence of the foyaitic type in most batholiths and stocks.[1] Bowen has explained this by supposing that the separation of the alkali magma takes place under suitable conditions when the residual liquid is squeezed out from a crystal mesh under the action of external pressure. It appears from the field evidence in Girnar that the concentration of volatiles may play an important part in the separation of the residual alkali magma. Both temperature and pressure will affect the equilibrium of the dissociation of the polysilicate, but the concentration of the volatiles may be the determining factor in this process. It is probable that in most granite batholiths the volatiles are distributed more or less evenly throughout the mass, whereas the actual concentration at any one place is not sufficiently high to effect the dissociation and separation of the alkali magma by the process contemplated above. The fractional crystallization of a smaller mass under suitable conditions of intrusion may concentrate all the volatiles into a small residual feldspathic liquid which will fulfil the necessary conditions for the separation of the alkali-rich magma. This will also explain why nephelite-syenite is found to occur in such laccoliths in comparatively small masses.

IMMISCIBILITY

The separation of a magma into two immiscible phases in the liquid condition has been regarded as one of the possible causes of differentiation. A consideration of the distribution of the rock masses shows that olivine-gabbro occurs at the margin in contact with the basalt, and the intermediate rocks occupy the central mountain. The granophyre intrusion in the surrounding hills originates from some depth and represents the lighter acid differentiate which was apparently left over after the cyrstallization of the basic rocks above. In its larger aspects this igneous complex does not show a separation of the magma into different layers according to their specific gravities, and it is difficult to see how the concentric arrangement could be brought about by liquid immiscibility with the lightest phase at the bottom, which was later intruded

[1] R. A. Daly, "Genesis of the Alkaline Rocks," *ibid.*, Vol. XXVI, No. 2 (1918), p. 129.

into the surrounding hills in the form of granophyre. It is possible that the conditions which may bring about the separation of two liquid phases in a silicate melt did not exist in this reservoir.

CRYSTALLIZATION DIFFERENTIATION

The facts of the case appear to be in better accord with the scheme of crystallization differentiation suggested by Bowen. He assumes that the parental magma is generally basaltic in composition, from which his rock types are derived, although this is not essential to his theory. The large masses of basaltic flows in Kathiawar render such an assumption plausible in the case of the Girnar magma. An attempt was made to calculate the approximate volumes of the different rocks from the published maps on the scale of 1 inch to a mile, supplemented by field notes. The base of the laccolith is not visible, and the calculation was made down to the ordnance datum-line corresponding to the mean sea-level, the average height of the basaltic plain being about 400 feet. The denudation of the rocks has been ignored, as cappings of basalt are preserved at various places, and the removal of the basaltic covering appears to be the principal work accomplished by erosion. Further, since all the rocks have suffered simultaneous erosion, the error due to this neglect in the relative proportions of the original volumes will be correspondingly lessened. The figures thus obtained are sufficiently close to give us an idea of the composition of the original magma (see Table I). Although no chemical analyses have yet been carried out for these rocks, a rough calculation for the silica percentages can be made on the basis of published analyses of rocks of similar mineralogical composition. Taking the lower figures for silica from such rock analyses, it is clear that the parental magma shows an intermediate character approximating to the silica percentage of diorite. This is in agreement with the general chemical composition of laccoliths studied in other places.

Whatever may have been the nature of the parental magma, the first rock to crystallize out was olivine-gabbro. It is curious that there was evidently no tendency for the heavy minerals to settle down by gravity, as all the gabbro occurs on the margin of the intrusion directly in contact with the basalt, and no concentration of

the heavier minerals has been observed in the lower parts. There are some indications in the field which may explain why the early formed heavy minerals did not sink to the bottom. The junction of olivine-gabbro with basalt is well exposed in several localities,[1] and it is found that no extensive veins of the former penetrate into the joints and cracks in basalt at the junction, which may be taken as evidence of the high viscosity of the original magma. Further, the intrusion was covered with more than 1,000 feet of basalt, and a simple calculation of the rate of transmission of heat through conduction shows that the cooling must have been extremely slow. This eliminates the possibility of convection currents due to rapid

TABLE I*

Rock	Areal Extension in Square Miles	Volume in Cubic Miles
Olivine-gabbro (including biotite-olivine gabbro)	12.0	3.0
Diorite and monzonite	1.7	.62
Granophyre	7.9	1.93

* Intrusions of syenite and nephelite-syenite form a negligible part of the total mass

cooling. Another possible cause of such a disturbance, namely, the settling of crystals, was also absent. Thus it appears that crystallization took place slowly in a viscous magma undisturbed by convection currents, and under such conditions the surface-tension forces may have combined with viscosity to counteract the tendency to sink by gravitational forces. The banding in the olivine-gabbro which is disclosed on the weathered surfaces and which is so conspicuously exposed at Lhasa Pawan at a height of about 2,000 feet is also difficult to understand by a process of crystal settling. It is probable that rhythmic crystallization, which has been observed in the laboratory,[2] may also be occasionally effective in the case of igneous magmas. The first-formed mineral or minerals, according to this hypothesis, crystallize out in a layer, and a concentration of the material takes place at the newly formed surface in obedience to physico-chemical laws, rendering a zone in the neighborhood com-

[1] One good locality is Kori Bara Ridge, Lat. 21°33′ N., Long. 70°32½′ E.

[2] M. Vorlander and J. Ernst, *Zeitschrift für physikalische Chemie*, Vol. XCIII, (1919), p. 52.

paratively poor in those molecules. The next layer of these crystals would thus be formed at some distance, where the solubility limit is again exceeded. A repetition of this process will give bands of the crystallizing mineral in the silicate melt. A high degree of viscosity in the medium with a slow rate of diffusion and quiet crystallization would appear to be essential conditions for the success of this process, and these conditions were on our assumption fulfilled by the gabbro-magma.

In the present condition of our knowledge regarding the exact mode of differentiation, it will perhaps be more useful to visualize a probable mode of intrusion and differentiation which will meet the requirements of the field in our case. The magma was basic or subbasic in composition, with a high viscosity which prevented the settling of the first-formed crystals. Cooling began on the margin of the dome under quiet conditions with the crystallization of magnetite, olivine, augite, calcic feldspars, and some biotite. The residual magma, with the volatiles, concentrated toward the bottom and the center. At this stage a fresh upward movement took place causing a further elevation of the top of the dome. Secondary reactions between the early formed minerals and the liquid resulted in the enrichment of biotite at the expense of olivine in the gabbro. Hyperthene was probably also formed as a result of silication of olivine. The development of a green pyroxene and hornblende may also be partially due to reactions with the minerals of olivine-gabbro. Brown augite partially changed to hornblende in sections of a lamprophyre between Gomukhi and Bhairo Jap, and the green augite of monzonite also gives indications of a similar alteration. Thus the intermediate phase of diorite and monzonite represents crystallization from and reactions with a liquid which had grown rich in alkali, silica, and volatiles and which also brought about important changes in the rock in contact at its borders.

It is probable that at depth the monzonite of Maliparab Kund will show transition to a quartz-bearing type. Specimens brought up from wells at the foot of the hill near Bhaveshwar are indicative of an abundance of quartz-feldspar rock coarsely crystallized, from which quartz-felsite or granophyre would differ mainly in its finer texture. The mother-liquor was thus gathered at the bottom, and its intrusion into the surrounding hills may mark a fresh movement

filling up and widening the circular cracks caused by the previous elevations. The probable derivation of nephelite-syenite from quartz-feldspar rock has already been dealt with in detail.

ORIGIN OF LAMPROPHYRE

The geological map accompanying this paper shows a girdle of basalt round the neck of central Girnar. It has already been noted that in hand specimens the lamprophyres rich in hornblende are difficult to distinguish from basalt except where the needles of hornblende are sufficiently long to be visible to the naked eye in the dark groundmass. While there is little doubt that the main mass contained in this girdle consists of basalt which has escaped denudation, very intimately connected with it occurs lamprophyre, especially in connection with nephelite-syenite intrusions. In the field the occurrence gives the impression that the lamprophyre is a metamorphosed phase of basalt, the metamorphism being due to the action of volatiles emanating from the associated nelpheite-syenite. However, veins of hornblende-lamprophyre occur in the central mass alone or along with feldspathic intrusions, and it is more probable that the source of this rock lay in the local segregations of small hornblende crystals in the magma. The same conclusion is reached from the fact that hornblende, green pyroxene, and the accessory mineral sphene, which are present in the lamprophyres, are also important constituents of the central mass of monzonite and diorite.

The broad conclusions arrived at as a result mainly of field study are sufficient to show the importance of Girnar from the point of view of magmatic differentiation. Further information in the way of mechanical and chemical analysis of rocks suitably chosen would undoubtedly be of great value in the elucidation of the principles of petrogenesis in this area.

Grateful thanks of the authors are due to His Highness the Nawab Sahab of Junagadh for providing forest guides during the survey of these hills. They also wish to acknowledge the helpful collaboration of Mr. H. L. Chhibber, late of the department of geology, Benares Hindu University, during the early reconnaissance in June, 1924, the mapping of the area having been completed during the months of May and June in the following year.

THE ORIGIN AND SIGNIFICANCE OF PITTED OUTWASH

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ABSTRACT

Deposits made by glacial streams following a comparatively rapid retreat of the ice from a region of irregular topography buried many isolated ice remnants. When these masses of ice melted, they formed pits in an outwash plain; locally the pits were so abundant that no level surfaces remained. Pitted outwash is compared with other glacio-fluvial deposits that have a somewhat similar topography, with the conclusion that there is danger of confusion with kames. The results of readvances of the ice over outwash before the ice blocks had all melted is discussed. Attention is called to factors that controlled the relative abundance of glacio-fluvial deposits and to the significance of pitted outwash as a criterion of relatively recent glacial retreat before its formation, thus distinguishing recessional from terminal moraines. Examples of the various types of deposits are given.

THE PROBLEM

Many geologists are familiar with the origin of glacial outwash and of terminal and recessional moraines, but few seem to realize the danger of confusion of these two types of deposits, particularly of pitted outwash with kames. The writer now knows that he has committed this mistake in the past and feels convinced that others have done likewise. The present paper is justified not only on scientific grounds but also because of the economic importance of correct discrimination of these two kinds of glacio-fluvial deposits.

DEFINITIONS

Outwash is the deposit of glacial streams on land. The material is sand and gravel which decreases in coarseness with increase of distance of transportation, is well sorted, and for the most part horizontally stratified. Kames are hills of assorted glacial drift in terminal and recessional moraines; their material is poorly assorted and is irregularly bedded with faulting and disturbance not at all uncommon. The material varies from fine sand to bowldery gravel and the texture changes greatly in short distances. Kames were formed for the most part on land and in some cases in small pools, but everywhere close to the ice margin. The term should not be applied either

to deltas formed where the ice margin was in standing water or to hills of dissected outwash formed at some distance from the glacial front.

PITTED OUTWASH

That some outwash deposits do not have a plane surface but contain pits or kettles has been realized by many geologists. The best detailed description of such topography that has come to the attention of the writer is that by Fuller.[1] Following in general his classification, the following types of pitted outwash may be distinguished: (*a*) plains with shallow or irregular depressions free from bowlders, (*b*) plains with deep kettles free from bowlders, (*c*) plains with deep kettles and other irregularities with bowlders, (*d*) plains with elongated or valley kettles or with chains of kettles, and (*e*) areas where kettles are so numerous that there is little or no plain between them. The deeper pits were all caused by the melting of buried blocks of ice, as were some of the shallower depressions that scarcely deserve the name of kettles. In the latter case the block may have been thin or it may have been deeply buried. Presence of bowlders has been taken to mean that the ice masses projected above the gravels, and in general such must have been the case, for the ice contained débris which on melting formed till, and in addition its presence allowed the underlying till to be preserved without a covering of assorted drift. It should not, however, be thought that all bowlders in pitted outwash deposits were thus derived, for many came either from drift hills buried by the outwash or from icebergs. Nor were all depressions caused by ice blocks; some of the shallower and less regular in outline represent basins due to stream scour or to redistribution of the sand by wind before vegetation obtained a foothold. The extreme levelness of many outwash plains is in considerable part due to a coating of loess which, unlike the interglacial fossiliferous loess, was derived from adjacent floodplains and newly deposited drift. Small elevations adjacent to kettles were explained by Fuller as material dropped or washed from projecting ice blocks. The writer has not discriminated such in Wisconsin although they may well account for some of the hitherto unexplained irregularities of certain out-

[1] M. L. Fuller, "Geology of Long Island, New York," *U.S. Geol. Survey Prof. Paper 82* (1914), pp. 39–44.

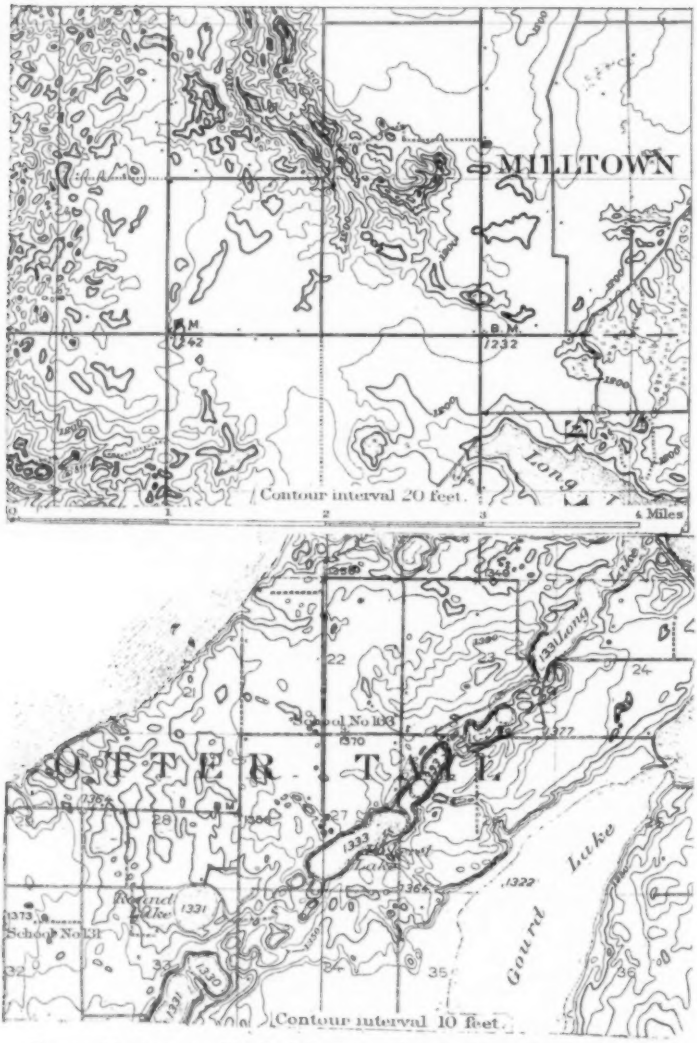

FIG. 1.—Upper: part of St. Croix Dalles quadrangle, Wisconsin, showing moraine at left and pitted outwash plain with kettle valley at right. Lower: part of Battle Lake quadrangle, Minnesota, showing chain of kettles and some ground moraine hills rising through the outwash.

wash plains. Kettle valleys and chains (Fig. 1) are explained by the fact that ice lasted longest in valleys and other depressions of the pre-existing surface, where it was thicker than above adjacent hills. The cases of extreme pitting of outwash plains, so that little is left of the original surface, mean that the gravels were deposited over a nearly continuous sheet of stagnant ice of irregular thickness. In topography of this type the presence of more or less till and bowlders

FIG. 2.—Kettle in pitted outwash plain, Sec. 7, T. 39, R. 30 W., Dickenson County, Michigan, showing moraine-like topography below the level of the outwash plain whose even sky-line is well seen below the distant hills. The resemblance of this kettle to a blocked valley is also shown. Photograph by W. O. Hotchkiss.

should excite no surprise, for wherever the ice projected there would be no gravels, and moreover there may be some drift hills that rose above the outwash level. Large kettles show similar knob- and sag-topography in their bottoms (Fig. 2).

MATERIALS

Pitted outwash plains, with the exceptions noted above, do not differ from other outwash in materials. Near to kettles, and where all of the deposit was let down by the melting of underlying ice, stratification was disturbed or entirely destroyed. Where bowlders are present, and particularly where slumping and weathering have mingled the assorted materials with loess, the resulting mixture is

very like till. In some places blocks of ice must have melted before the completion of the outwash deposition, and the resulting pits then were filled with deltaic gravels. Examples of this type have not as yet come to the attention of the writer in the course of field work, although they most certainly exist.

TERRACES

Terraces of pitted outwash were formed in the same manner as ordinary outwash terraces, that is, by change in the grade and the load of the streams so that they eroded what they had formerly deposited. Decrease in load is a normal consequence of recession of the ice margin and was accompanied by a decrease of the stream grade. Other causes of changes in the slope of streams were (*a*) formation of lakes by glacial retreat, with consequent clearing of the waters so that they could erode to a low grade, (*b*) erosion of lake outlets, allowing lower levels of cutting above the lakes, (*c*) melting of ice blocks, either in the outwash or in valleys beyond the deposits, and (*d*) opening of new lower outlets by melting back of the margin of the glacier itself. All these phenomena were normal accompaniments of glacial wastage and must have been developed to their maximum extent in interlobate areas where two glaciers adjoined. In reconstructing successive ice margins from drainage phenomena it is well to recall that isolated stagnant masses of ice that formed no moraines were just as effective in blocking drainage as was the main body of the glacier. The results of changes in the grades of streams were (*a*) broad, flat-topped terraces of degradation, (*b*) large, steep-sided valleys through areas where formerly deposition had prevailed, (*c*) shallow lake basins due to irregular stream scour in these valleys, and (*d*) coarse gravels and bowlder pavements concentrated by erosion of the finer materials. Fuller describes terraces formed by streams flowing in kettles by the sides of partially melted ice blocks. In many instances terracing and erosion of drainage channels took place before all the masses of ice had melted.

SIMILAR TOPOGRAPHY

Pitted outwash plains with relatively few depressions cannot very well be mistaken for other types of glacio-fluvial deposits. Errors have been made in mistaking very much pitted plains for

either kames or till moraines, and in confusing kettle chains with valleys blocked by moraines. In the former case discrimination may be made by (*a*) better assortment of the material in outwash than in kames, (*b*) fairly even local skyline in the outwash, (*c*) presence of occasional mesa-like remnants of the original plain at elevations higher than the majority of the hilltops, and (*d*) outline of the outwash area which, as it occupied low ground leading away from the ice front, is apt to be elongated in a direction normal to that of the moraines. In some cases where considerable till is present and drift hills rise through the outwash, correct determination is well-nigh impossible, but given fair exposures of the material there is little reason for mistaking the two classes of deposits. In the case of kettle valleys and chains the matter is simpler. To ascribe them to blocking of interglacial valleys in the gravels would involve the assumption that the ice deposited material only in the valleys and not at all on the flat uplands, which is manifestly absurd. Such chains do reflect the position of pre-existing valleys, but do not imply that the obstructions in them were wholly due to ice deposition. Glacial deltas formed at the ice front contain kettles,[1] but below the surficial topset beds the stratification is inclined toward the lake or sea. Pits in lake sands from the partial burial of stranded icebergs are possible where the waters retired before waves and currents filled the depressions; if such occur the slopes of the sides of the pits would be rather gentle because of the presence of water. Laminae of lake clay would be present between the layers of sand. No examples of pitted lake plains are known to the writer.

ECONOMIC ASPECTS

From the economic standpoint the well-sorted outwash deposits are much superior to kame gravels, which they locally resemble in topographic form. It is true that some of the pitted outwash has lost its stratification, but this is of little importance. Areas of pitted outwash require much less test-pitting than do the more variable kames, and development can proceed with much more assurance of success than in either morainal material or eskers. As with other gravel de-

[1] H. L. Fairchild, "Kettles in Glacial Lake Deltas," *Journal of Geology*, Vol. VI (1898), pp. 589–96; W. M. Davis, "Structure and Origin of Glacial Sand Plains," *Bull. Geol. Society of America*, Vol. I (1890), pp. 195–202.

posits, the angle of slope is a rough index to the coarseness of the gravels in pitted outwash; very coarse gravels may have a slope of as much as 35 degrees. Use of this criterion, in connection with poor development of vegetation on coarse gravels, is of great value to the road-material geologist.

OVERRIDDEN PITTED OUTWASH

Some outwash deposits appear to have been overridden by a readvance of the ice before all of the buried ice masses had melted. These have a rolling to level till-covered upland surface with scattered moraine-like depressed areas around the margins of some of which the gravels outcrop. The arrangement of these sunken knob and sag spots is unlike that of recessional moraines. Gravel is found at irregular depths beneath the till, for some kettles were filled as a result of early melting of the ice masses in them. In general the larger ice blocks must have lasted the longest, and therefore melted after the second retreat of the glacier from that area. In some cases eroded drainage channels may have survived the deposition of the till without filling, since they extended in a direction parallel to that of the motion of the ice; later ice drainage may have been able to reopen some of these valleys. In this manner plateau-like ground moraine elevations with scattered rough patches and occasional deep valleys may have originated. Somewhat similar results would have followed overriding of pitted outwash of a previous glacial stage, but in this case (*a*) the till covering would have been undisturbed by melting of ice masses in the underlying gravels, (*b*) erosional valleys in the older outwash would be much more extensive than valleys due to glacial waters and would be reflected in the final topography, and (*c*) beyond the border of the later ice outwash would have buried much of the older pitted gravels.

DISTRIBUTION OF PITTED OUTWASH

As with all glacio-fluvial deposits, pitted outwash is most abundant in regions where the glacial drift is stony and sandy. This composition of the till which furnished the material for the glacial waters to assort is dependent primarily upon the character of the bed rocks from which the ice obtained its load and, to a lesser degree, upon the

presence of older water-sorted Pleistocene deposits. Crystalline rocks formed many large bowlders; limestones and dolomites made cobbles and pebbles; and sandstone furnished sand. When it is realized that the bulk of the drift was not carried very far we can readily see why the drift of southern Wisconsin, a dolomite and sandstone region, differs from the drift of Iowa and Illinois, where the bed rock is the Coal Measures shales. This difference in character of the till is reflected in the topography; not only does stony till form steeper slopes than clay till, but its presence determines the abundance of pronounced topographic features like kames, eskers, and pitted outwash. The regions of clay till are nearly devoid of glacio-fluvial deposits, not because of any difference in drainage conditions or manner of glacial action, but because there was little coarse material for the waters to concentrate. That the younger drift sheets have progressively more and more glacio-fluvial deposits is explicable by the correspondingly greater and greater amount of stone in the tills. As suggested by Sardeson,[1] this came about because the first glaciers advanced over preglacial residual soils and weathered bed rocks, while the later ones found many previously stripped fresh ledges and considerable assorted drift.

SIGNIFICANCE OF PITTED OUTWASH AS A CRITERION

The ice blocks that formed the kettles in pitted outwash varied in size from a few yards to several miles in diameter. Masses of such size were necessarily derived from the wastage of glacial ice in situ, for it is very unlikely that large icebergs could have floated in the shallow aggrading streams of the outwash plains. The number of isolated ice blocks left on the retirement of the main body of the glacier was determined by (*a*) the rapidity of melting, and (*b*) the irregularity of the underlying surface. While it is true that rapid melting would quickly destroy exposed ice blocks, this factor was offset by the great rapidity of deposition of the fluvial materials which was a necessary result of such melting. Preservation of ice in depressions of the underlying surface caused a certain degree of reflection of the older topography in the form of the surface after the melting

[1] F. W. Sardeson, "Glacial Drift Sheets of Minnesota," *Pan-American Geologist*, Vol. XXXVIII (1922), pp. 383–402.

of the ice remnants. In this way the outlines of older valleys, in part altered by deposition of till before the formation of the outwash, are discerned in the shape of elongated kettles and chains of kettles. Presence of pitted outwash in front of a moraine is indubitable proof that the glacier extended beyond the moraine at a date not very many years before its formation. Judging from observations in Alaska, buried masses of ice might have lasted for more than ten years, but even the largest could not have survived a major recession and readvance such as marked the intervals between the several glacial stages. Therefore the presence of pitted outwash serves to distinguish recessional from terminal moraines, save in the case where the maximum stand of the ice of a glacial stage remained too short a time to form a terminal moraine. A moraine behind a well-developed pitted plain is the product of a comparatively rapid recession of the ice front, and not of a readvance of any considerable magnitude.

EXAMPLES

Pitted outwash plains are very common in Minnesota, Wisconsin, Michigan,[1] and northeastern Illinois, where the kettles contain many of the numerous lakes of those states. Many of these plains are very sandy and some are covered by sand dunes. An example of a pitted plain that is well known to students of topographic maps is that shown in the northeastern part of the St. Croix Dalles quadrangle in northwestern Wisconsin (Fig. 1). Profiles from this map are shown in Figure 3. This area was mapped as pitted outwash by R. T. Chamberlin,[2] but when studied by the writer in 1908 it was interpreted as a gravel plain that had been overridden by the ice with the formation of a complex of morainic deposits that blocked the interglacial valleys. Restudy of the region in 1920, when better exposures had been opened by road grading and the excavation of gravel pits, showed conclusively that Chamberlin's interpretation of the topography was correct and that this is an immense pitted outwash plain which extends to the inner edge of the terminal moraine many miles to the east.

[1] I. C. Russell, "The Surface Geology of Portions of Menomonie, Dickinson, and Iron Counties, Michigan," *Michigan Geol. Survey Report, 1906* (1907), pp. 64–72.

[2] R. T. Chamberlin, "The Glacial Features of the St. Croix Dalles Region," *Jour. Geol.*, Vol. XIII (1905), pp. 238–56.

Farther south in Wisconsin Alden[1] has described a number of pitted outwash plains and terraces, and has worked out the changes in drainage that led to the erosion of the higher levels. Profiles of some of these are shown in Figure 3. Some of the best examples are in the vicinity of Oconomowoc. The writer is inclined to class more of the area as pitted outwash than did Alden, for although the higher surfaces are not quite as level as are the lower terraces, the material is all fairly well sorted gravel, and the summits between the kettles range themselves into several distinct levels even where there is little left to suggest an original terrace surface. The glaciers on either side of this interlobate area acted as dams in retaining the glacial streams; opening of successively lower and lower outlets by ice recession led to the erosion of the morainic borders and of considerable portions of the higher terraces.

At the residence of the late ex-Governor Phillipp, on Sauk Prairie, near Prairie du Sac, Wisconsin, there is a kettle in outwash about a mile outside of the terminal moraine. This is explained by a temporary advance of the Wisconsin ice before the formation of the moraine and its attendant outwash, for a layer of till was encountered in drilling a well on the west bank of the pit. Were it not for this we might possibly account for the phenomenon by an iceberg in a lake shut in the valley to the west by a dam of outwash, although it would be difficult to see how so large a mass of ice could have escaped from the glacier across the deltaic plain.

Examples of the use of pitted outwash in determining the margin of the last drift have been noted by the writer at Brooklyn and east of Hudson, Wisconsin. In both localities outlying fresh drift had been tentatively ascribed to an earlier glacial stage, but presence of pitted outwash plains between this drift and the recognized Wisconsin moraine makes a strong case for the correlation of this marginal drift as not much older than the moraine. The evidence is stronger at Hudson than at Brooklyn. Without doubt this criterion would be of much help in many other localities.

Observations by the writer favor the idea that the broad uplands north of Lake Geneva, Wisconsin, are pitted outwash plains which

[1] W. C. Alden, "The Delavan Lobe of the Lake Michigan Glacier," *U.S. Geol. Survey Prof. Paper 34* (1905), pp. 44–62; "Quaternary Geology of Southeastern Wisconsin," *U.S. Geol. Survey Prof. Paper 106* (1918), pp. 263, 274.

were overriden by a readvance of the ice. Gravel is found beneath the till over a wide area, and the presence of immense pits, such as

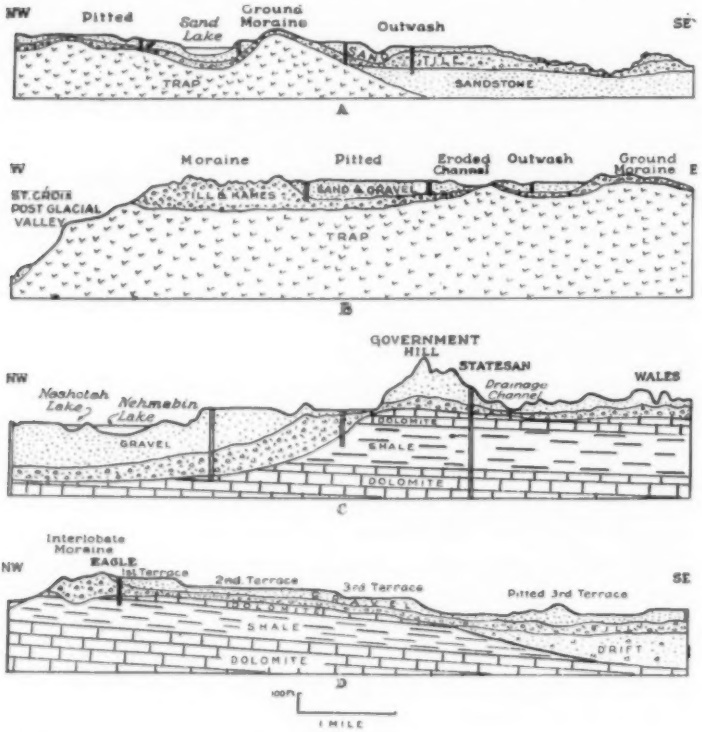

FIG. 3.—Profiles showing pitted outwash plains.

A. St. Croix Dalles quadrangle, Wisconsin, showing ground moraine hill rising through gravels and total destruction of original surface to southeast.

B. St. Croix Dalles quadrangle, Wisconsin, showing relation of pitted outwash to terminal moraine and to ground moraine.

C. Oconomowoc quadrangle, Wisconsin, showing interlobate gravels and pitted gravel terraces with eroded drainage channel.

D. Eagle quadrangle, Wisconsin, showing eroded outwash terraces described by Alden, and relation of outwash to interlobate moraine.

the basin of Lake Geneva, is apparently best explained by the suggestion that the readvance occurred before the largest ice masses had

time to melt. The region east of the village of Lake Geneva is interpreted by the writer as pitted outwash rather than as terminal moraine. The combination of older buried outwash with younger pitted outwash which is cut up by deep drainage channels makes this area very difficult to decipher.

The list of notable occurrences of pitted outwash might be extended almost indefinitely; doubtless a resurvey of southeastern Wisconsin, which was so thoroughly mapped by Alden, now that such an enormously greater number of exposures are available, would result in extending the area of pitted outwash at the expense of moraines. This revision would have considerable economic importance, but would not affect his conclusions as to recessional positions of the ice margin to a material extent. Not all plains that appear to be covered with till were actually overriden by the ice. Near Wittenberg, Wisconsin, road-material parties have explored an area that appears to be pitted outwash which has been weathered to a depth of several feet; this has destroyed the bedding and stained the sands so that they resemble till. Such weathering is not uncommon in flat sandy areas like this.

Gilbert[1] and Tarr and Martin[2] have described the formation of modern pitted outwash in front of the Hidden Glacier in Alaska with ice blocks still melting at the time of investigation.

[1] G. K. Gilbert, "Glaciers and Glaciation," *Harriman Alaska Expedition*, Vol. III (1904), p. 64.

[2] R. S. Tarr and Lawrence Martin, "Alaskan Glacier Studies," *National Geographical Society Magazine* (1914), pp. 148–51.

FAUNAL ZONES IN THE STANDARD MISSISSIPPIAN SECTION[1]

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ABSTRACT

The standard Mississippian section is that exhibited in the Mississippi Valley, exposed in Iowa, Illinois, and Missouri. In this section there are recognized a series of more or less distinct faunal zones which have been observed to have considerable geographic distribution. These zones are defined, the leading features of their faunas are mentioned, and their known geographic distribution is shown, with the belief that the facts presented may assist in the wider correlation of the Mississippian formations and faunas.

Just as the Devonian section of New York State has come to be considered the standard for that period in North America, so the Mississippian section as exposed in Iowa, Illinois, and Missouri is the recognized standard for this period. Although highly important observations on the section in localities within this region had been made by David Dale Owen, B. F. Shumard, and others in the early fifties of the last century, the first really comprehensive description of the section was the one offered by James Hall, which appeared in its final form in 1858, in his Iowa report. During the earlier years of study of this important series of limestone strata, they were known commonly as the "Carboniferous limestone," the "Sub-Carboniferous limestone," or the "Lower Carboniferous limestone," being combined with the overlying coal-bearing series or "Coal Measures," in the so-called "Carboniferous system." Winchell was the first to suggest the use of the geographic name Mississippi for this limestone series, but the term Mississippian, as it is now used, was first proposed by H. S. Williams in 1890.

The work of James Hall was confined more especially to the state of Iowa and the adjacent localities in Illinois, and his description of the lower formations of the series, which are especially well exhibited in these localities, is much more complete than his de-

[1] Published by permission of the directors of the Geological Surveys of Illinois and Kentucky.

scription of the higher formations. He did, however, make an excursion in company with his assistant, Mr. A. H. Worthen, along the Mississippi River bluffs south from St. Louis, in Illinois, and on the basis of the observations made at this time he described the higher formations in his *Iowa Report.* Hall's classification and nomenclature of the lower formations of the Mississippian has remained with only somewhat minor changes down to the present time, but profound changes have been made in the limitations and nomenclature of the higher portion of the series.

For fifty years after the appearance of Hall's *Iowa Report,* his section was accepted as standard, although some writers preferred to make use of a different name for the uppermost formation of the section. From time to time some writers suggested certain modifications, and some new formation names were suggested, but they found little or no recognition in the general literature on the subject.

It was not until early in the present century that additional detailed work upon the Mississippian formations was inaugurated, which has brought out a vast amount of information concerning the several formations and their faunas, especially those of the upper half of the system. This work was started by the Geological Survey of Illinois and has been carried on continually for nearly twenty years by that Survey, and more recently with close co-operation with the surveys of Iowa, Missouri, and Kentucky, until at the present time detailed geologic maps on the fifteen-minute quadrangles of the United States Geological Survey as a base have been essentially completed from St. Louis, Missouri, to Princeton, Kentucky. This work has led to the breaking up of the uppermost formation in Hall's classification, the Kaskaskia—or the Chester, as Worthen and others have preferred to call it—into sixteen distinct formations which are alternately sandstone and limestone-shale members. All of this work has led to the recognition of two distinct series in the Mississippian system, a lower or Iowa series comprised almost wholly of limestone formations, and an upper or Chester series comprised of alternating sandstone and limestone-shale formations. These two major divisions of the Mississippian are reflected in both the stratigraphy and the paleontology of the system.

In the course of these Mississippian studies a number of well-

defined faunal zones have come to be recognized, which are widely distributed throughout the more typical exposures of the limestones, and some of which have been detected in more or less distant, outlying districts. Since it is more than likely that at least some of these zones may be discovered in still farther outlying regions, it seems to be desirable to outline them in a manner sufficiently clear to make the information serviceable to those who may be engaged in detailed work on Mississippian stratigraphy and paleontology.

Not all of the zones which will be considered here have hard-and-fast limits identical with the formational boundaries which are recognized, although in general they are limited more or less closely by the stratigraphic units which we designate as "formations." The succession of life in any sedimentary series such as that under consideration is somewhat comparable to the passengers on a local railroad train. At every station there is some change in the personnel of the passengers, at the larger stations more change than at the smaller ones, but nowhere is there a complete change. Certain passengers are boarding the train, and others are leaving it at all stops. Some ride only from one station to the next, others continue for a longer distance, and a few may continue throughout the entire journey. A large number of passengers are likely to remain the same before and after any single local stop, but when the personnel at the beginning of the journey and at the end are compared, an almost or entirely complete change is likely to have taken place. Those fossils which are comparable to the passengers who ride only from one station to the next are the ones which best qualify for recognition as the narrower-zone markers. Other forms which are like the passengers who remain on the train past two or more stations characterize broader zones. For the purposes of the geologist it is the narrower zones which are most serviceable in local studies, and it is some of these narrower zones especially which will be considered here in detail, although some of the broader zones will be discussed also.

In a consideration of the faunal zones present in the Mississippian system, it is only the limestone or limestone-shale formations which need to be taken into account. The sandstone formations which are so conspicuous a feature in the Chester series of southern

Illinois and western Kentucky only rarely contain marine fossils of any sort, so they may be disregarded entirely. The formational units which will be taken into account in the following discussions are as follows:

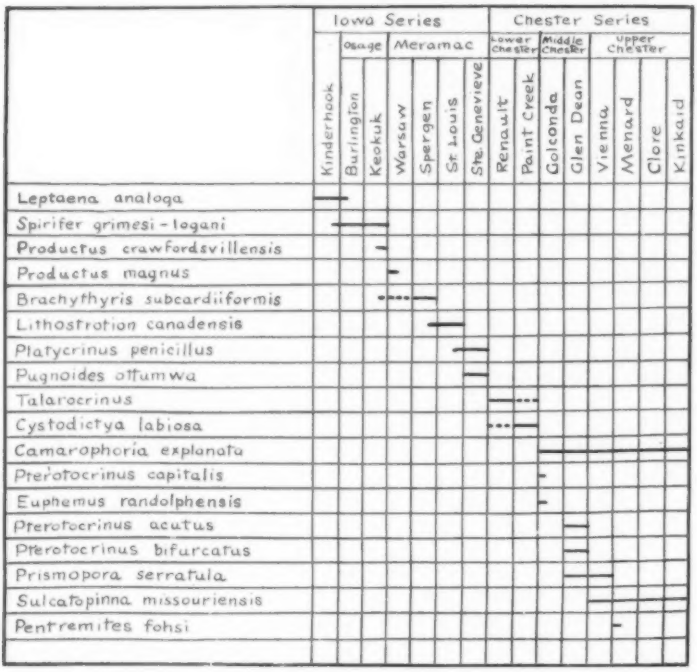
CHESTER SERIES OR UPPER MISSISSIPPIAN	IOWA SERIES OR LOWER MISSISSIPPIAN
15. Kinkaid limestone	7. Ste. Genevieve limestone
14. Clore limestone	6. St. Louis limestone
13. Menard limestone	5. Spergen limestone
12. Vienna limestone	4. Warsaw limestone
11. Glen Dean limestone	3. Keokuk limestone
10. Golconda limestone	2. Burlington limestone
9. Paint Creek limestone	1. Kinderhook group
8. Renault limestone	

In the accompanying table these several formations are represented by the vertical columns, and the names of the fossil forms which are of particular zonal value are placed at the left of the table, the heavy black lines representing the position in the stratigraphic column of the zone of each of the fossils named. In a few cases zone fossils will be considered which do have some range beyond their main zonal limits; such conditions are indicated by dotted lines in the table.

I. *Zone of "Leptaena analoga."*—The Kinderhook group comprises the lowermost division of the Mississippian series in the Mississippi Valley region. This series of sediments is not a unit formation, neither are the Kinderhook faunas a unit. The group consists of various limestones, shales, and sandstones of more or less local geographic distribution. These various formations represent the accumulation of sediments in a sea advancing over a land surface, and the Ozark land is most closely associated with this sedimentation. Differences in the constitution of the surface of this land in different parts, in the residual materials to be worked and redeposited by the advancing waters, and perhaps other factors, controlled the various Kinderhook sedimentary units, and likewise the distribution of the life. Under these circumstances it is difficult to select any one fossil species which is a good zonal representative for the basal Mississippian. *Leptaena analoga* has been selected, not

because it is present in all Kinderhook faunas, for it is not, although it does occur rather commonly and in many different situations, and because the basal Mississippian, including the Kinderhook and the lowermost Burlington, is distinctly the last appearance of this long-

TABLE I



range brachiopod type in America. This form is a close relative of *Leptaena rhomboidalis*, and, as that species has been interpreted by many authors, would be joined with it. Brachiopods of this type, commonly identified as *L. rhomboidalis*, are not uncommon in the Middle Devonian faunas of America, but are nearly or quite wanting from all of the Upper Devonian faunas. After this disappearance it comes in again in several of the Kinderhook faunas and continues into the very basal portion of the Burlington limestone, after which

it makes its final exit from our faunas. This Lower Mississippian *Leptaena* zone is recognizable not only in the Mississippi Valley region, but also in the northwest, in the southwest, and in the more eastern portion of the United States. It is believed that the strata containing this faunal element are essentially contemporaneous throughout their whole distribution.

II. *Zone of "Spirifer grimesi-logani."*—These two members of the genus *Spirifer* are representative of a group of species which are characterized by their large size, by their rather narrow, bifurcating plications which are similar in character throughout the entire surface of the shell, including the fold and sinus, and by the presence of fine radiating striae over the whole surface except on the cardinal area. *Spirifer logani*, which is the higher of the two forms, differs from *S. grimesi* in being proportionally broader, but the two species apparently merge one into the other. Another species in the same group is *S. rowleyi*, which differs from *S. grimesi* in its more sharply angular mesial sinus. All of these shells are close relatives of the European *S. striatus*, and perhaps some European paleontologists would include all of them under that specific name. This type of *Spirifer* characterizes very definitely a life-zone in the standard Mississippian section of the Mississippian limestones, *S. grimesi* being especially characteristic of the Burlington limestone and *S. logani* of the Keokuk limestone. *S. rowleyi* is commonly present in the Fern Glen formation, which is a manifestation of the very lowest Burlington, and it is apparently present also in some of the uppermost Kinderhook beds. This faunal zone is recognizable as far away as Montana to the northwest, and New Mexico to the southwest, and it exists also to the east of the Cincinnati arch, and the inclosing sediments are all believed to be referable to the same time interval.

The basal portion of this life-zone merges into the higher portion of the *Leptaena* zone beneath it. It is believed to be essentially contemporaneous with the *Spirifer striatus* zone in the mountain limestone of England, and in the Carboniferous limestone of Belgium, the faunas of these distant regions having numerous identical, or at least closely related, species of brachiopods in common.

This zone is one of the most conspicuous crinoidal horizons in the whole sedimentary series of America, and on the basis of some

of the crinoid species it may be subdivided into a number of subzones, but because of the usual imperfection of preservation of this class of fossils, such subzones are not as readily recognizable, except locally, as is the larger zone characterized by the *Spirifers*.

III. *Zone of "Productus crawfordsvillensis."*—This is really a subzone of the last one, and its known geographic distribution is far more limited. It seems to be desirable to mention it, however, because it is so conspicuous a horizon in the more southern portion of the area occupied by the Mississippian limestones in the Mississippi Valley, but it has not been recognized in the section north of St. Louis. It occupies a position in the upper portion of the Keokuk limestone, and especially in southeastern Missouri the species occurs in great numbers wherever the proper horizon is exposed. Another species which is uniformly associated with *P. crawfordsvillensis* is *Spirifer mortonanus*, but it never occurs in so great numbers. Other more widely distributed species in the same faunule are *Orthotetes keokuk*, *Spirifer logani*, and *Tetracamera subtrigona*.

The species *Productus crawfordsvillensis* was originally described from the Crawfordsville, Indiana, locality from which so many beautifully preserved crinoids have been recovered, and here, as in the Mississippi Valley on the opposite side of the Illinois basin, *Spirifer mortonanus* is a constant associate. Although the character of the sediments in the two localities is not at all alike, the similarity of the faunal association is sufficient to give assurance of the existence of the same life-zone and of their essential contemporaneity.

IV. *Zone of "Productus magnus."*—One of the most noteworthy faunal assemblages in the Mississippian limestones of the southern portion of the Mississippi Valley basin is that which is characterized by *Productus magnus*, the largest member of the genus in this region. The species varies considerably in the numbers of individuals which occur. In some localities hundreds of specimens can be gathered, while elsewhere in the same zone only an occasional example can be found. The species has nowhere been observed outside of this limited zone in the Mississippi Valley. Associated with this species and not found elsewhere, but occurring much less frequently, is the large and coarse pelecypod known as *Aviculopecten amplus*. Other shells com-

monly present in the same association, locally in large numbers, are *Syringothyris subcuspidatus* and *Spirifer washingtonensis*.

The species occurring in this zone were originally referred to the Keokuk limestone, but the more recent detailed studies in southeastern Missouri and southwestern Illinois have shown that this zone lies above the Keokuk limestone and is the representative of the lower portion of the Warsaw limestone of the Upper Mississippi Valley.

The fauna of the *Productus magnus* zone in all of its purity has been collected as far to the southeast as Casey County, Kentucky, where the same association of *P. magnus*, *A. amplus*, and *S. subcuspidatus* are present in gray crystalline limestone which is entirely similar to much of the rock containing the same fauna in Illinois and Missouri. Typical examples of *Productus magnus* are also known from southwestern Missouri. From this distribution the continuity of this faunal zone, in contemporaneous beds representing the lowermost portion of the Warsaw time interval, is apparently established throughout the region extending from southwestern Missouri to east-central Kentucky.

V. *Zone of "Brachythyris subcardiiformis."*—The faunal zone characterized by *Brachythyris subcardiiformis* is not so sharply defined as in the zone of *Productus magnus*. This species has been reported from the Keokuk limestone in Iowa, but at least in southern Missouri and Illinois, it is a highly characteristic member of the fauna of the Spergen or Salem limestone, possibly occurring in the higher portion of the Warsaw, but nowhere as low as the distinctive *P. magnus* zone. One of the associates of this species is *Spirifer lateralis*, but this species is much less common and has a more limited range, a little below the main horizon of *B. subcardiiformis*. This faunal zone is recognizable as far away as southwestern Missouri, southern Indiana, and central Kentucky.

VI. *Zone of "Lithostrotion canadensis."*—The species of compound corals which commonly have been referred to *Lithostrotion canadensis* and *Lithostrotion proliferum* always have been considered as being characteristic of the St. Louis limestone. This conclusion is not strictly justified, however, for specimens of *L. canadensis* are occasionally met with in strata which are certainly late Spergen or

Salem limestone in age. This *Lithostrotion* zone, however, is a well-developed one in the Mississippian limestones of the interior of North America, and is chiefly confined to the St. Louis limestone. The zone is a widely distributed one, being recognized in Iowa, western and eastern Missouri, Illinois, western and eastern Kentucky, southern Indiana, eastern Tennessee, northeastern Alabama, and northwestern Georgia. This is the most widely distributed zone characterized by compound corals in the Mississippian of the interior of North America, and while there are three or four other species of this sort locally present in the Mississippian limestones of this region, none are comparable in any degree with the widely distributed *Lithostrotions*.

In places in the St. Louis limestone the colonies of *Lithostrotion* occur in such numbers and are so crowded together as to suggest a genuine reef habit. Elsewhere the species is scattered here and there in isolated colonies. In some areas they can be found with a little search in almost any exposure, but in other regions, some of which are of considerable extent, diligent search fails to uncover a single example.

VII. *Zone of "Platycrinus penicillus."*—Lying next above the *Lithostrotion*-bearing beds in the standard Mississippian section is a zone which is characterized by the little crinoid which has been called both *Platycrinus huntsvillae* and *Platycrinus penicillus* in the literature. The latter of these names has priority in publication and therefore is the proper one to use. All species of *Platycrinus* have a distinctive stem which is elliptical in cross-section, and which is twisted so that the longer axis of the ellipse changes position in each successive stem segment. *P. penicillus* is further characterized by the presence of a series of peripheral spines upon each stem segment so that the species can be recognized from isolated stem joints, a condition which is not usual among crinoids. The basal plates also of this species are characteristically marked by three radiating ridges, and in consequence they are easily identified. The strata of the Ste. Genevieve limestone are nearly everywhere characterized by the remains of this crinoid, although it is not limited to this formation, the species being first present in the higher portion of the St. Louis limestone. The species is not everywhere present in abun-

dance throughout the zone which it characterizes, in some beds at some localities it cannot be found at all, but in most exposures of any considerable extent a diligent search of the weathered surfaces will disclose at least some of the characteristic stem plates and perhaps a base or two. In other localities the remains of the species are present in more or less abundance.

Associated with *P. penicillus*, and so far as known confined exclusively to the Ste. Genevieve limestone, is the little brachiopod *Pugnoides ottumwa*, which is also a most excellent marker for this zone. In places this species is present in abundance, but throughout considerable areas it has not been observed at all, and on the whole it is less widely distributed than are the *Platycrinus* plates.

The underlying *Lithostrotion* zone and the *Platycrinus penicillus* zone overlap to some extent, for the crinoid occurs in association with or in limestone strata beneath beds bearing *L. canadensis*, but this coral has not been observed occurring in any beds of undoubted Ste. Genevieve limestone. In the higher portion of the Ste. Genevieve limestone, however, especially in Kentucky, there is a narrow subzone characterized by the compound coral known as *Lithostrotion harmodites*, although a critical study of the species will doubtless show that it is not congeneric with *L. canadensis*.

The *Platycrinus penicillus* zone, characterized either by specimens of this crinoid or by the shells of *Pugnoides ottumwa*, or by both, has been recognized from Iowa to Alabama, and consequently is one of the widely distributed faunal zones of the Mississippian.

VIII. *Zone of "Talarocrinus."*—With the exception of a single species, *Talarocrinus simplex*, which is known from the Spergen or Salem limestone, the genus *Talarocrinus* is confined to the Lower Chester formations. *T. simplex* does not closely resemble the several Chester species of the genus, most of which are strikingly alike in their two basal plates, whose joining suture is situated in a distinct furrow, giving the base a strongly bi-lobed appearance. *T. simplex* has a smooth, hemispherical base, and it is more than probable that a critical study of the species will show that it is not truly congeneric with the Chester species.

The *Talarocrinus* zone, confined chiefly to the Renault limestone of the Lower Chester, but also occurring, though much more rarely

in the next succeeding Paint Creek limestone, is clearly recognizable from St. Clair County, Illinois, the northernmost extent of any of the Chester formations in the Mississippi River bluff sections through southeastern Missouri, southern Illinois, Kentucky from west to east, eastern Tennessee, and northeastern Alabama. This *Talarocrinus* zone clearly represents a contemporaneous horizon throughout the whole region where it is known to exist, and is the lowermost faunal zone of the Chester series. In the Mississippi River sections the limestones containing this fauna are separated from the Ste. Genevieve limestone with its *Platycrinus penicillus* fauna, by the thick Aux Vases sandstone, which lies with a distinct unconformity upon the subjacent limestone. In southeastern Illinois and throughout Kentucky, Tennessee, and Alabama, the Aux Vases sandstone is lacking from the section, and the *Talarocrinus*-bearing limestone rests directly upon the *P. penicillus*-bearing beds, with an important unconformity, although the unconformity is obscured in many places and the line of separation between the two limestones is difficult to determine with certainty because of the lithologic similarity. The base of the Renault limestone of the Chester series invariably can be established, however, within the limits of a few feet, by a careful search for the two zone fossils which have never been found in association, although a number of other long-range species do pass from the lower to the higher fauna.

IX. *Zone of "Cystodictya labiosa."*—The *Cystodictya labiosa* zone and the *Talarocrinus* zone are essentially coextensive stratigraphically, and together they include the Renault and Paint Creek limestones of the Lower Chester. There is this difference between the two zones, however: *Talarocrinus* has its great development in the Renault limestone, becoming rare and in most localities wanting in the Paint Creek, while *Cystodictya labiosa* is comparatively rare in the Renault, becoming abundant in the Paint Creek. Neither of the species is known to survive the Paint Creek. Like the *Talarocrinus* fauna, the *Cystodictya labiosa* zone has been recognized from southeastern Missouri and southern Illinois to Alabama.

In southern Illinois and in the more northern portion of Kentucky, both east and west of the western coal fields, the Renault limestone is separated from the Paint Creek limestone by the Bethel

sandstone, mistakenly called Sample sandstone by some writers east of the coal fields. To the south this sandstone has thinned, and south of the coal fields it has disappeared so that the Renault and Paint Creek limestones occur in one continuous sequence, although they are readily enough separated by their faunas. In central Kentucky the *Cystodictya* fauna is not in evidence, although it may be discovered with more detailed field studies, but it reappears away to the southeast in Alabama.

X. *Zone of "Camarophoria explanata."*—The life-zone characterized by this little brachiopod differs from those which have been mentioned already in that it has a much greater stratigraphic range, and also in the fact that it includes a number of lesser zones which will be mentioned later. The horizon of introduction of this species of *Camarophoria* seems to be uniform throughout the Mississippi and Ohio valleys, in southern Illinois, southeastern Missouri, and western and central Kentucky. Its appearance in the Chester series still farther south, in Tennessee and probably in Alabama, also seems to be contemporaneous with its earliest occurrence farther north. The really important fact concerning this shell is its introduction, for after having made its appearance it continues to live on and to reappear in fauna after fauna of the Chester, up to the highest limestone of the series. Its first appearance is in the beginning of the Middle Chester, and its lowest position is commonly in the Golconda limestone, although it has been collected in one locality in southwestern Illinois, in a fossiliferous phase of the Cypress sandstone.[1] In the hundreds of collections which have been made in the Paint Creek and Renault limestones of the Lower Chester, not a single example of *Camarophoria explanata* has been observed, and the place of introduction of the species is an important horizon to be established in any Chester section.

XI. *Zone of "Pterotocrinus capitalis."*—The massive, more or less subglobose, detached wing plates from the vault of this species of crinoid are highly characteristic of the lower portion of the Golconda limestone, in the basal part of the Middle Chester. Complete examples of this crinoid are exceedingly rare, and so far as known to

[1] Collected by Mr. R. S. Poor, of the Geological Survey of Illinois, in Union Co., Ill.

the writer the holotype, used in the original description of the species by Lyon, is the only such specimen that has been collected. The massive wing plates, however, occur in places in great numbers, and less frequently the semicircular basal plates are found. The species is closely restricted to the lower portion of the Golconda limestone where it is commonly associated with the earliest occurrence of *Camarophoria explanata*.

The genus *Pterotocrinus* is almost the last representative of the Camerate crinoids, and is a highly specialized form. It is related to and is a successor of the genus *Talarocrinus* in the Lower Chester. The most peculiar feature of the genus is found in the occurrence of five so-called "wing plates" standing vertically and radiating from the vault above the five groups of arms. The several species of the genus are characterized especially by different sorts of wing plates, and in places these plates have been fossilized in great numbers, even though no other portion of the crinoid is recognizable.

Pterocrinus capitalis has been collected from almost every Lower Golconda limestone locality from the Mississippi River bluff sections in Union County, Illinois, all the way across southern Illinois, and continuing in Kentucky to Caldwell County. It has not as yet been observed south and east of the western Kentucky coal field, but Butts[1] has reported it from Lookout Mountain in eastern Tennessee, from the same horizon. Neither has the species been collected from the more northern exposures of the Golconda limestone in Randolph County, Illinois.

Associated with *P. capitalis* and restricted to the same horizon is another species of the same genus, *P. coronatus*, but this is a much less common form. Another faunule which occurs in strata associated with the beds carrying *P. capitalis* but not always including that species includes a highly interesting group of mollusks, both gastropods and pelecypods, most of which are as yet undescribed. This faunule is particularly characterized by *Euphemus randolphensis* and *Nucula platynotus*, and is more widely distributed in Illinois than is *P. capitalis*, for it is present in Randolph County as well as in the more southern counties, and is typically represented as far east as Caldwell County, Kentucky. This molluskan faunule is not

[1] *Ky. Geol. Surv.* (Ser. 6), Vol. VII (1922), p. 171.

so commonly met with as is *P. capitalis*, but it may be considered as one phase of the same life-zone.

The faunas of the lower part of the Golconda limestone are perhaps the most prolific in the whole Chester series in Illinois and western Kentucky. Besides the forms which have been mentioned there are numerous brachiopods, a host of bryozoans, and many pentremites, and a number of the species are restricted, so far as known, to this horizon.

XII. *Zone of "Pterotocrinus acutus" and "P. bifurcatus."*—The wing plates of these two species of *Pterotocrinus* are entirely different from those of *P. capitalis*. In the first species mentioned they are elongate, gently curved, and spinelike; in the second one they bifurcate at the end in a peculiar manner. Neither of the species has ever been found in association with *P. capitalis*, and they have been collected only in the Glen Dean limestone. They characterize a faunal zone everywhere higher in the Chester series than that of *P. capitalis*. Although these species are not present in all exposures of the Glen Dean limestone, either one or both of them have been collected from localities distributed all the way from Randolph County, Illinois, to Caldwell County, Kentucky. Both of them have been collected from the same limestone in Breckenridge County, Kentucky, east of the western Kentucky coal field, and both were originally described from Pulaski County in the southeastern part of Kentucky. A number of other fossil species are likewise more or less characteristic of this same zone. One of the most useful forms to the stratigrapher is the bryozoan *Prismopora serrulata*, which occurs most abundantly in this zone but which does occur rarely in the Upper Golconda limestone, and locally it is somewhat common in the Vienna formation which is the limestone next higher in the series than the Glen Dean. Another bryozoan, *Archimedes laxa*, is most commonly present in the Glen Dean limestone, but it does occur at both lower and higher horizons. The blastoid *Pentremites brevis* has been found only in this zone where it is widely distributed and is common locally. Another species of the same genus, *P. spicatus*, is also restricted to this zone, but it is less common than the last. There are still other species, mostly bryozoans and blastoids, which are useful to the stratigrapher in the identification of this faunal

zone, but the ones which have been mentioned are those which have been proved to be most serviceable.

XIII. *Zone of "Sulcatopinna missouriensis."*—The formations lying above the Glen Dean limestone comprise the upper division of the Chester series, and in this division the lesser faunal zones are not so distinct as are those in the Middle and Lower Chester. The limestones in this upper division, from the lower to the higher, are the Vienna, the Menard, the Clore, and the Kinkaid. Throughout all of these limestone formations one of the fossils which is most serviceable to the stratigrapher is the pelecypod *Sulcatopinna missouriensis*. This shell perhaps is most characteristic of the Menard limestone where it occurs locally in considerable numbers. It is less commonly met with in the other formations. Associated with this *Sulcatopinna* throughout the Upper Chester is the brachiopod *Composita subquadrata*. This species is related to *C. trinuclea* of the Middle and Lower Chester, a species which is much smaller and narrower and which possesses a more conspicuous fold and sinus. There is some intergradation between the two species but in general they are not likely to be mistaken.

There are subordinate faunal zones within the larger *Sulcatopinna* zone, but they are characterized by certain combinations of species rather than by one or a number of characteristic species. In the Vienna limestone shells of the *Sulcatopinna* are present, as well as other species commonly met with in the Menard limestone, but not infrequently numbers of examples of *Prismopora serrulata*, the bryozoan which is so highly characteristic of the Glen Dean limestone, are associated with the pelecypod. This is an association of species which would not be looked for either in the Glen Dean limestone below or in the Menard limestone above. In the Clore limestone lying above the Menard there are likely to be numerous examples of the little bryozoan *Batostomella nitidula*. Although this species is not confined to the Clore but has been identified in most of the Chester-limestone formations, it nowhere is known to occur in such numbers as are present in some places in this formation.

At the present time no distinctive species or association of species has been recognized for the Kinkaid limestone, although the fauna of this formation, perhaps, has been less carefully studied than those

of the older formations of the series. In general, the fauna is much like that of the Menard limestone, and, in some places, because of the similarity in lithology and fauna the two formations may be indistinguishable unless the stratigraphic relations can be determined.

XIV. *Zone of "Pentremites fohsi."*—Perhaps the most important of the subzones of the *Sulcatopinna missouriensis* zone, so far as they have been recognized, is the zone of *Pentremites fohsi*. This species is a highly characteristic member of the genus to which it belongs, characterized by its large size as well as by its configuration. It is widely distributed throughout southern Illinois and western Kentucky, and is strictly limited, so far as it has been observed, to the basal portion of the Menard limestone. A species which is associated with it and which is almost as good a marker of the zone is *Pterotocrinus menardensis*, known only from its large, flat, more or less subcircular wing plates, and nearly everywhere they are found these species are associated with numerous examples of the peculiar, spinose, vault plates of a species of the crinoid genus *Hydreionocrinus*. This zone is commonly the most prolific in fossils of any portion of the Menard limestone, and its fauna includes a large variety of bryozoans as well as numerous species of brachiopods and other forms which are more or less common throughout the Upper Chester formations.

The faunal zones which have been considered in the foregoing pages certainly are not all that are recognizable, and it is altogether likely that some have been omitted which may prove to be as useful as those which have been mentioned. These zones, however, are the ones which have proved to be of greatest service stratigraphically in connection with the detailed mapping of the Mississippian formations which has been in progress in Illinois, Missouri, and Kentucky during the past decade and a half.

THE KEAIWA OR 1823 LAVA FLOW FROM KILAUEA VOLCANO, HAWAII[1]

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ABSTRACT

The Keaiwa lava on Kilauea is the oldest lava flow recorded by white men in the Hawaiian Islands. It is remarkable among the many flows from Kilauea because it welled out from a crack 6 miles long, spreading out seaward in a flow which is in places only a few inches thick. The absence of cinder or driblet cones along the crack indicates that the usual fire fountains of Hawaii did not play during this eruption. Attached to the walls of the crack in many places are lava balls that resemble bombs but do not owe their form to projection. Two phreatic explosions occurred along the crack immediately after the eruption.

INTRODUCTION

Kilauea Volcano is located on the Island of Hawaii, the largest island of the Hawaiian group, which lies in the Pacific Ocean between 19° and 22° north latitude, and between 18° and 22° west longitude. The Island of Hawaii has been formed by five volcanoes —Kohala, Mauna Kea, Hualalai, Mauna Loa, and Kilauea—the last three of which have erupted in historic time. The great dome of Mauna Loa rises 13,675 feet above sea-level and is crowned by the caldera of Mokuaweoweo. Kilauea forms a low dome 4,040 feet high on the southeast side of the dome of Mauna Loa. On the summit of Kilauea is a shallow lava-floored basin about 3 miles in diameter. In the southwest portion of this basin or caldera is the yawning pit of Halemaumau—"The House of Everlasting Fire."

Halemaumau is usually occupied by a lake of fiery lava which rises and falls according to the state of activity of the volcano. After long intervals of time the quiet lake of lava disappears and sometimes explosions result. Thus in 1790 and in 1924 explosions occurred which hurled huge blocks of rocks into the air and sent up

[1] Published by permission of the Director, United States Geological Survey. The writer is indebted to F. C. Calkins, of the Geological Survey, for constructive criticism of this article.

cauliflower clouds laden with ash and steam several miles into the air.[1] At times the subsidence of the lake has been followed by the opening of fissures on the flanks of the dome from which lava has poured out. These fissures on the slopes of Kilauea do not occur at random but are limited to two definite rift zones, one of which has a general trend to the east and the other to the southwest from Halemaumau.

The eastern slope of Kilauea is well watered by moisture precipitated from the northeast trade winds and hence is largely covered with a tropical jungle. As the winds pass over the top of the mountain they cease to drop their moisture. This meteorologic condition causes the Kau Desert on the leeward or southern and western slopes of the dome.

Flow after flow of lava from the high dome of Mauna Loa has buried the north slope of Kilauea so that it is possible that, within the next century, lava from Mauna Loa may flow into the crater of Kilauea. The great re-entrant in the south coast line of Kilauea is due to the downfaulting of that portion of the dome below the surface of the Pacific Ocean. For a distance of 6 miles, south of the caldera of Kilauea, the slope is about 250 feet to the mile, but in the remaining 3 miles to the coast, there are two fault escarpments over 1,000 feet high. Southwestward these escarpments die out and are veneered by the recent flows from the southwest rift zone.

This rift zone is a fissured shallow graben from 1 to 2 miles wide extending from Kilauea southwestward to the sea. It is from fissures in this zone that many great eruptions have occurred in recent times. For months during 1920 lava flowed in this region from the Maunaiki[2] (Hawaiian for Little Mountain). Maunaiki, the cone built by the 1920 eruption, is a low dome 70 feet high covering an area of about 1 square mile. The lava from this dome flowed to the margin of the flow through a set of ramifying tubes. Most of the lava, when it froze, formed the smooth billowy, *pahoehoe* type of lava which

[1] H. T. Stearns, "The Explosive Phase of Kilauea Volcano, Hawaii, in 1924," *Bull. Volcanologique, International Geophysical Union*, Naples, Vol. II, Nos. 5, 6 (1925), pp. 193–209. *Ibid.*, "The 1924 Eruption of the Hawaiian Volcano," *Scientific American*, Vol. CXXXII, No. 4 (April, 1925), pp. 242–43.

[2] See *Monthly Bulletin Hawaiian Volcano Observatory*, January to June, 1920.

changes at the extremities to the bristling and jagged *aa*[1] type. The flow of 1920 moved forward only a few feet a day so that people were able to witness it at close quarters.

A type of eruption on Kilauea more common than the outbreak of 1920 is that of the 1921 eruption on the floor of the caldera. At that time a fissure opened and low fountains of lava played from it. The scoriaceous lava clots that piled up around the fountains form a line of driblet or spatter cones. Many lines of driblet cones 10–50 feet high can be seen in the southwest rift zone of Kilauea. Cones 50–150 feet high consisting of loose cinders formed by the extrusion of medium fluid lava highly charged with gas are found on Kilauea. The Kamakaia cones are of this type.

In general the lava eruptions of Kilauea build either low domes like Maunaiki, driblet cones such as were built in 1921, or cinder cones similar to the Kamakaia Hills. The flows from any one of these types of cones are usually less than 25 feet and more than 5 feet thick.[2]

LOCATION AND AREA

The Keaiwa or 1823 lava flow on Kilauea is unique among the hundreds of flows from this volcano because it is the first one recorded by white men. Although similar, perhaps, in texture and composition to some other flows, it is unusual because of its source, the manner of its extrusion, and its thinness. It covers an area of 5 or 6 square miles in the Kaalaala and Kapapala lands, in the Kau district, on the southwest slope of Kilauea, 12 miles from Halemaumau. (See Fig. 1.) The flow issued from the Great Crack, a fissure 6 miles long and 2–30 feet wide, one of the series of cracks that mark the southwest rift zone of Kilauea. It is known locally as the Keaiwa flow and covers a triangular area with the base at the sea and the apex 6 miles to the northeast, in the Kilauea section of the Hawaii National Park. It is accessible to hardy tourists, being crossed by the Kau-Puna trail $1\frac{3}{4}$ miles from the Volcano Road.

[1] The type of lava flow with a relatively smooth surface, often with a satiny or shiny crust that moves forward by projecting one tongue after another is called *pahoehoe*.

The *aa* type of lava flow consists of a field of bristling, jagged, and jumbled blocks that have been produced by the granulation of a stiff, overcooled fluid on the point of solidifying.

[2] The crater of Kilauea and its associated lava flows are well shown on the Kilauea, Pahala, and Puna contour maps of the Geological Survey.

DISPUTED IDENTITY AND EXTENT OF FLOW[1]

The location and extent of the Keaiwa flow have been shown on maps in many different ways, and there is every reason to believe that none of the old records regarding the eruptions were consulted in connection with the mapping. Moreover, the areas were not surveyed but merely hachured on the maps as incidental to the land surveying. A comparison of the Hawaiian Government land maps from 1885 to date shows some remarkable changes in dates and areas for the several flows, especially the flow of 1823. Thus the Keamoku flow from Mauna Loa is shown on one map as the flow of 1823 and represented as flowing down over Kilauea into the sea. Another map shows it separated into two flows, one originating on Mauna Loa and the other on the southwest slope of Kilauea, the latter called the Kamooalii, dated 1823, and shown as if it had flowed into the sea.

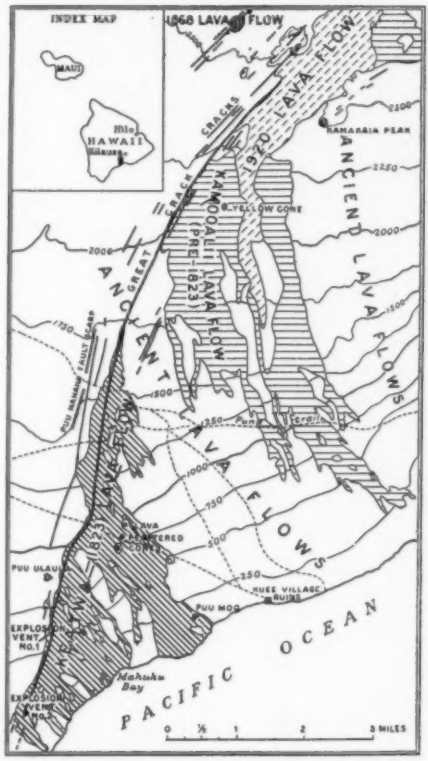

FIG. 1.—Map showing the Great Crack and the lava flow of 1823. Base map by U. S. Geological Survey.

[1] W. O. Clark, of Pahala, Hawaii, first noticed the inconsistencies of maps and descriptions for the date of this flow and concluded that it was the flow of 1823 (oral communication to the author, May, 1924).

Hitchcock[1] disputes the areas and dates of the lava flows shown on one map but in the same publication accepts and reproduces another map without question. This map[2] shows the flow of 1823 as the flow of 1868, and the Kamooalii flow as the flow of 1823 and as reaching the sea. The map was originally prepared by E. D. Baldwin, a land surveyor, who surveyed the region in 1907. Baldwin, in a letter to Hitchcock,[3] gives no evidence to support the date he assigns to the flow marked "'68 crack" except his own opinion, based on the fact that it issued from a fissure and the record that the flow of 1868, some 6 miles to the north, issued from a fissure, and also the fact that both flows are black and fresh in appearance. A field examination of the flow marked by Baldwin "'68 crack" shows that on account of the topography the eastern lobe must have had two sources. Hitchcock himself recognized this dilemma.[4] A field examination shows also that the Kamooalii flow (assigned by Baldwin to 1823) is represented incorrectly as reaching the sea. Both W. O. Clark and the writer have ridden entirely around the Kamooalii flow and thus proved without doubt that it never reached the sea. (See Fig. 1 for correct boundaries of this flow.) The Kamooalii flow therefore cannot be the flow of 1823 because historic records, cited below, show that the flow in 1823 reached the sea and burned a canoe.

Ellis[5] describes the flow of 1823 as witnessed by the natives as follows:

> The people of Kearakomo also told us that no longer than five moons ago Pele [Hawaiian goddess of volcanoes] had issued from a subterranean cavern, and overflowed the lowland of Kearaara [Kaalaala] and the southern part of Kapapala. The inundation was sudden and violent, burnt one canoe, and carried four more into the sea. At Mahuku the deep torrent of lava bore into the sea a large rock, according to their own account near a hundred feet high, which, a short period before had been separated by an earthquake from the main pile

[1] C. H. Hitchcock, *Hawaii and Its Volcanoes*, Hawaiian Gazette Co., Honolulu, 1909; "Hawaiian Earthquakes of 1868," *Seismol. Soc. America Bull.*, Vol. II, No. 3 (September, 1912), pp. 181–92.

[2] C. H. Hitchcock, *Hawaii and Its Volcanoes*, 1909, pl. 26, p. 163.

[3] *Ibid.*, pp. 209–10.

[4] *Ibid.*, p. 208.

[5] William Ellis, *Journal*, Hawaiian Gazette Co., Honolulu, T. H., 1917 (reprint of 1827 edition, p. 200).

in the neighborhood. It now stands, they say, in the sea, nearly a mile from shore, its bottom surrounded by lava, its summit rising considerable above the water.

On Figure 1 is shown the location of Mahuku Bay, 4 miles from Kamooalii flow. It is surrounded, however, by the Keaiwa flow.

Ellis[1] further describes the flow of 1823 as follows:

> It was highly scoriaceous, of a different kind from the ancient bed of which the whole valley was composed, being of a jet-black color and bright variegated lusters, brittle, and porous; while the ancient lava was of a gray or reddish colour, compact, and broken with difficulty.

This is a very exact description of the flow of 1823 as mapped by the writer. The Kamooalii flow, on the other hand, is partly the massive blue *pahoehoe* of the dense type and partly the slow-moving type of *aa* 5–10 feet thick with a decided brown color due to decomposition. Its source is far above the Ponahoahoa Chasms, the place where Ellis visited the source of the flow of 1823. The Kamooalii flow is of the sluggish type which cools quickly and hence could not have reached the sea in time to burn a canoe. Additional evidence was gathered from an old Hawaiian named Pelelili, who resides at present in Wood Valley near Pahala, about 4 miles northwest of the Keaiwa flow. He said he crossed the Keaiwa flow (1823) in 1856, when he moved to Wood Valley from Puna.

Moreover, in 1868 Dr. William Hillebrand and Rev. Titas Coan both searched for the flow of 1868, and Mr. Coan found and mapped it. It is scarcely possible that either of these men could have passed through the region without seeing or hearing about the Keaiwa flow had it occurred in that year. Moreover, Coan frequently made trips into the Kau district after 1868, hence it is exceedingly unlikely that the Keaiwa flow was extruded after his visit in 1868, or else he would have recorded it. Three important trails cross the Keaiwa flow, and the natives at Kuee would have had to cross it in order to reach Kapapala. Certainly, if it had been freshly poured out they would have told about it, and Coan or other whites who spoke Hawaiian fluently would have recorded it.

After a thorough investigation, the writer has concluded that both the areas and dates of the flows shown in Baldwin's map re-

[1] *Ibid.*, p. 165.

produced by Hitchcock are in error, that the Kamooalii flow is prehistoric, and that the Keaiwa flow should be dated 1823.

CHARACTERISTICS OF THE FLOW

Near its source the flow consists of black *pahoehoe* from 1 to 12 inches thick and extremely vesicular. A few hundred feet from the fissure the *pahoehoe* crust is broken and turned on end like slush ice in an ice jam. Farther seaward it becomes *aa*, bristling with jagged and formidable points. Nowhere does the flow average more than 5 feet in thickness, and for the first half mile from the fissure it is only a few inches to 2 feet thick, leaving many kipukas[1] on level ground. (See Fig. 1.) The large number of kipukas on the uniformly sloping plain indicates the extreme fluidity of the lava at the time it was poured out.

A microscopic examination[2] of a specimen from this flow shows that it has the usual microlitic texture of the recent lavas of Hawaii, with large amounts of unindividualized ferritic material and some glassy base. It contains some sharply defined olivine crystals and a few clusters of plagioclase and augite, some of them with associated olivine grains. It is unusually vesicular as compared with other lava flows on Kilauea and is similar to the frothy flows that have issued from fissures on the top of Mauna Loa. Only three other flows from Kilauea are comparable to it. Its rate of movement for a given gradient must have been considerably greater than that of ordinary types of *pahoehoe* or *aa*. It seems to have issued from the fissure as a sheet of lava rather than as a narrow stream, and Ellis' statement that it burned a native canoe upon reaching the ocean indicates that it must have moved very rapidly. The south end of the fissure is only half a mile from the shore; hence it is safe to assume that the flow quickly reached the sea.

In several places the flow was confined to channels, and it happened that a row of old driblet cones stood at right angles to the direction of one of the main channels. As a result these cones, called Lava Plastered Cones (see Fig. 1), formed a dam to the flowing lava, thereby causing it to pond. In a few places it seems as if the

[1] Hawaiian word for an island-like area not covered by a lava flow.

[2] Made by Whitman Cross, United States Geological Survey.

molten lava actually flowed up the slopes of the cones. The dam held long enough for the ponded lava to crust over, but the lava soon found an outlet and drained seaward. The shore lines of this pond are now preserved on the slopes of the cones 5–34 feet above the present surface of the flow. The large cone just south of the Kuee-Kau trail has a thin crust of Keaiwa lava smeared over its entire northern slope and 34 feet above the present level of the flow. In a few places the lava spilled over the rim into the old craters of the driblet cones, and some of these streams flowed on seaward through a breach where lava had formerly found an exit at the time when these craters were active. Because of the veneer of 1823 lava it might be thought that these ancient cones had been active in 1823. The pond of lava must have drained rapidly, because the shore lines are preserved only at high levels. In places blocks of crust from the upper shore line slid down on the sides of the Lava Plastered Cones to the present level of the flow while the lava was still viscous, as is indicated by the "shark teeth" slickensides developed on the sides of the cones by the sliding crusts.

Tree molds 6 feet high are common on the upper part of the flow, which issued in a region previously covered with vegetation. These are thin shells of lava that cooled around trees. When the lava drained away the congealed lava molds remained standing. Some of the molds contain charcoal, and on some of them is preserved the impression of the tree bark, indicating that the lava chilled very quickly. Fragments of *ohio lahua* tree still occur on the surface of the flow near the molds, and most of them are only very slightly charred (see Fig. 2). On the edge of the flow, not more than 10 feet away, there are dead trees still standing that were killed by the heat. Ellis, who visited the flow a few days after its eruption, describes it as follows:

> The appearance of the tufts of long grass through which it had run; the scorched leaves still remaining on one side of a tree, while the other side was reduced to charcoal, and the strings of lava hanging from some of the branches like stalactites, together with the fresh appearance of the shrubs, partially overflowed and broken down, convinced us the lava had been thrown out only a few days before.[1]

[1] William Ellis, *Journal*, Hawaiian Gazette Co. (Ltd.), Honolulu, Hawaii, 1917 (reprint of 1827 edition, p. 165).

In places where thin streams of lava overflowed grassy areas the under surface of the lava is a mold of the grass and sticks on which it cooled (see Fig. 3).

A quarter of a mile south of Puu Ulaula and 500 feet west of the Great Crack there is a fissure 1,700 feet long which has been the source of a prehistoric flow and from which a small tongue of lava also has issued. The lava is black, fresh-looking *pahoehoe*, resembling in general the flow of 1823 with which, however, it is nowhere connected and cannot be definitely correlated. In all probability, however, this flow originated at the same time as the lava that issued in 1823 from the Great Crack, 500 feet away. (See Fig. 1.)

FIG. 2.—Tree mold in the 1823 lava flow with fragments of charred wood nearby. Photograph by Harold T. Stearns.

SOURCE OF THE FLOW—THE GREAT CRACK

The Great Crack is one of a number of open cracks that fissure the southwest rift zone, a belt 1–2 miles wide extending southwestward from Kilauea to the sea. Throughout most of its length (see Fig. 4) the Great Crack has the general appearance of a steep-sided trench 20 to 30 feet wide. A few yards north of the head of the Keaiwa flow the crack breaks up into many smaller ones. There are also graben areas which seem to have been produced by the separation of the fissure into two cracks for a short distance and the later collapse of the narrow slices thus formed, with the subsidence of the

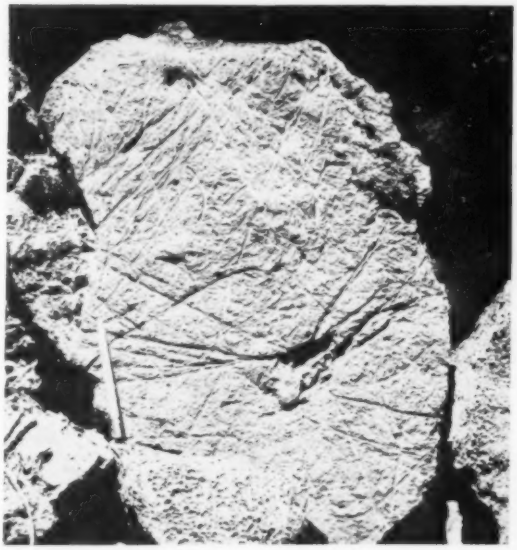

FIG. 3.—Grass impressions on the under surface of a cake of the lava of 1823 near the Great Crack. Pencil gives scale. Photo by O. H. Emerson. Courtesy of the Hawaiian Volcano Observatory.

FIG. 4.—The Great Crack from which the flow of 1823 issued. The trees grow in kipukas on older lava. Note the thinness of the flow. Photograph by Harold T. Stearns.

magma. In other places the graben is due to the collapse along the walls bordering the fissure when the region settled down after the extrusion of the lava. In a few places, especially near the sea, the Great Crack decreases in width to about 2 feet, and it finally dies out in échelon fashion at the coast. The cracks beyond the area of extravasation are only a few inches wide.

The Great Crack, which extends from 300 to 2,500 feet above sea-level, differs from the others only in its continuity; it can be traced continuously for about 8 miles, and before it was buried by the flow of 1920 it must have been traceable still farther toward Halemaumau. However, the mere fact that the Great Crack is continuous does not necessarily indicate that it was all opened at one time. There is ample evidence to show that it belongs to a system of fissures from which lava has poured out again and again. The Kamooalii flow and the flows of 1868 and 1920 issued from these fissures, and there is evidence that all the lava flows from the west side of Kilauea come from the same system.

The remarkable feature of the flow of 1823 is that it issued from the Great Crack along a continuous length of nearly 6 miles. This is unusual, because fissure eruptions in Hawaii tend to break out spasmodically from several parallel fissures at different altitudes. Evidence that lava issued from the entire length of the fissure is given by the occurrence of lava clots on both sides for the entire length. Furthermore, the topography of the area covered by the flow (see Fig. 1) makes it seem impossible that the flow should have originated in any one part of the crack. The walls of the fissure are plastered with a thin veneer of lava that froze on the walls as the lava subsided. The trickles and stalactites of lava that make up this veneer have been interpreted incorrectly by Powers[1] as proof that the fissure opened "as the flow was cooling." He also states that "the flow covers the country for one-fourth of a mile on either side of the opening." This is true in only one place along the entire length of the fissure. Everywhere else the flow is not more than a few yards wide, and in some places it extends only a few feet on the west side of the fissure, for the altitude of the surface prevented the lava from flowing farther in that direction.

[1] Sidney Powers, "Tectonic Lines in the Hawaiian Islands," *Geol. Soc. America Bull.*, Vol. XXVIII (September 21, 1917), p. 508.

LAVA FORMS IN AND NEAR THE GREAT CRACK

The walls of the Great Crack, in many places, show not only frozen trickles of lava but also large numbers of spherical lava balls imbedded in a matrix of 1823 lava. (See Fig. 5.) The writer has called these spherical masses "lava balls" to distinguish them from bombs. They are more or less spherical and range in diameter from a few inches to 3 feet. Some of them are perfect spheroids—for example, the one illustrated in Figure 6 which is 85 millimeters ($3\frac{1}{2}$ inches) in diameter and was collected from a wall of the Great

FIG. 5.—Lava balls imbedded in the lava of 1823 lining the wall of the Great Crack. Photograph by R. H. Finch, Hawaiian Volcano Observatory.

Crack. They have been seen also in the walls of other fissures from which frothy *pahoehoe* of the same type has poured out.

These balls are formed in three ways. The lava clots thrown into the air during the extravasation of the lava are scattered at distances as great as 200 feet from the fissure, indicating that the fountaining was violent and spasmodic. As no spatter cones exist on the fissure, it is probable that the eruption did not continue for a long time at any one place. During the eruption some of the clots must have fallen back into the crack filled with hot lava, and, being somewhat viscous and hence heavier than the rising gas-impregnated magma, they sank into it in the same manner as the blocks of crust founder in the fiery lake of Halemaumau. As they sank the

clots grew by accretion into spherical masses, and when they floated up again were caught on the edge of the fissure, where they are exposed today. Others, doubtless, were carried away by the flowing lava. In Figure 7 is given a cross-section of the ball illustrated in Figure 6, showing its rind or skin and its core. The texture of the balls shows that the interior and skin are derived from the same

FIG. 6.—A lava ball from the Great Crack. Natural size

magma. The core, however, is more vesicular and has larger phenocrysts. This hypothesis for their origin seems to be the most tenable as no true bombs occur among the lava clots in or near the crack, and none of these balls are found free of the matrix.

Associated with these lava balls, and in outward appearance similar to them, are balls which, when broken open, reveal bits of foreign *aa* that have fallen into the magma from the walls of the fissure. While floating up to the surface these bits of *aa* acquired a skin of lava. Many of these balls measure 30 centimeters (1 foot) or more in diameter, and when broken open they are usually found

to contain several separate pieces of *aa* held together by a skin of the lava of 1823. The included fragments show no sign of fusion. About 20 feet below the brink of the crack there is exposed in some places a bed of red *aa* 5–8 feet thick made up of the typical loose fragments. Beds like this undoubtedly supplied the material for the cores of the balls of this type.

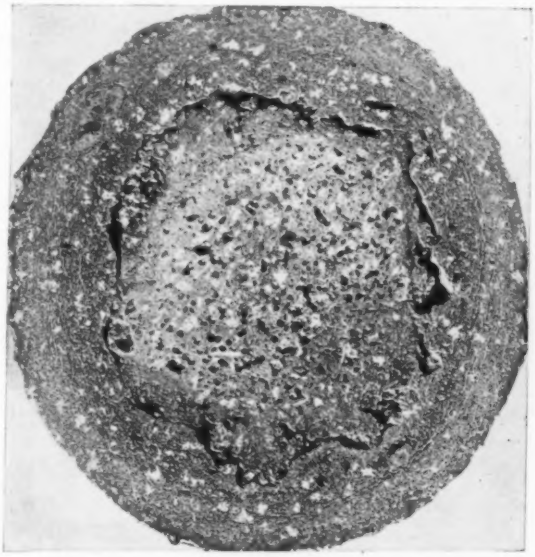

FIG. 7.—Cross-section of the lava ball shown in Figure 6. Natural size

Other balls contained angular blocks of dense, weathered *pahoehoe* that had fallen from the wall, received a coating of lava, and floated up in the same manner. Examination of the balls at ancient fissures somewhat similar to the Great Crack shows that they also originated in this way. The formation of the balls probably requires a magma of a specific consistency and temperature. Projecting portions of the walls of the fissure were coated over and formed parts of spheroids. As no fusion effects were found on the walls of the fissure or on the inclusions, it is concluded that the country rock chilled the magma rather rapidly.

Scattered along the Great Crack and at various distances from

it up to about 200 feet are large thin pancake-like clots of lava which resemble large cow dungs in appearance, especially as many of them are stained yellow from chemical action. They are about 30 centimeters (1 foot) in diameter and 1–3 centimeters ($\frac{1}{2}$–1 inch) in thickness. When removed from the *aa* their under surfaces are found to be perfect molds of the underlying rock with its irregularities. The fact that they do not form a continuous coating on the surface near the Great Crack indicates that they resulted from spasmodic eruption in the fissure.

PHREATIC EXPLOSIONS[1]

The eruption of 1823 was unusual because of the two phreatic explosions that occurred at two different places on the Great Crack immediately after the extravasation of lava. The explosion at vent No. 1 (see Fig. 1) was small, for it threw out accessory ejecta[2] most of which are less than 4 inches in diameter, and the area covered by the explosion débris lies within a radius of only 50 feet from the vent. The explosion at vent No. 2 was more violent, for it hurled blocks as large as 1 foot in diameter 200 feet from the vent. The large blocks all occur within 50 feet of the fissure, and the débris is more abundant on the southeast side. The average depth of the débris near the vent is only 3 inches. The blocks from this explosion fell on the lava of 1823, and practically all of them smashed through the frothy crust of the flow after it had cooled. In one place, however, a block was found frozen in the crust, indicating that some of the lava was still viscous at the time of the explosion, which therefore probably took place not more than an hour after the last lava was extruded.

[1] This term is used according to Suess's original definition to indicate explosions not accompanied by the ejection of fluid or incandescent materials.

[2] In his terminology of ejecta the writer follows J. H. Johnston-Lavis ("On the Fragmentary Ejecta of Volcanoes," *Geol. Assoc. Proc.*, Vol. IX [1887], pp. 421–32). He defines them as follows: (1) Essential ejecta are those materials that issue in a fluid state and consist either of the volatile constituents or the magma in which these are contained, that produced the particular emission in question. (2) Accessory ejecta consist of the older volcanic materials of the same vent, torn away, expelled, and mixed with the essential ejecta of an eruption. (3) Accidental ejecta consist of either volcanic materials from other centers, or sedimentary or other rocks of the subvolcanic platform, also torn out, expelled, and mixed with the two before-mentioned ejecta.

A detailed study of the gray, brown, red, and black ejecta torn from the walls of vent No. 2 leads to some interesting conclusions. None of the blocks showed any secondary fusion such as bread-crusting or glazing of their surfaces. A field examination of them showed an absence of essential ejecta. However, among the accessory ejecta were found a few fragments of limestone consisting of brecciated shells and coral. These are the first accidental ejecta ever found on Kilauea. The vent (see Fig. 1) is 280 feet above and only a little over half a mile from the sea. The presence of limestone among the ejecta demonstrates that there is a buried coral reef under this area. The area, therefore, must have been reclaimed from the sea by lava flows. As such reclamation is a common event on Kilauea and Mauna Loa, these ejecta should not necessarily be interpreted as part of a limestone platform extending under the island, as has been suggested by some earlier writers.

As no essential ejecta were found among the débris at the two vents, the explosions were undoubtedly phreatic. The source of the water that caused the explosions were probably the main water table of the island, which is at about sea-level under the vents.

SUMMARY

The Keaiwa flow of 1823 from Kilauea welled up in the Great Crack and spread out seaward as a thin flow, in places only a few inches thick. The absence of cinders or driblet cones in or along the crack indicates that the usual fire fountains of Hawaii did not play during this eruption. Lining the Great Crack in many places are lava balls that appear to be bombs, but that do not owe their form to projection.

After a field examination of the areas and sources of the various flows and a careful investigation of the maps and records regarding the flows dated 1823, it is concluded that the Kamooalii and Keamoku flows are both prehistoric and that the Keaiwa flow is the one that issued in 1823. Its extent and location are shown on the accompanying map (Fig. 1).

IRON-STAINED SANDS AND CLAYS

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ABSTRACT

It is pointed out that the distribution of color in a sediment is as important in determining the general color effect as is the total amount of coloring matter present. It is shown that quartz will become iron-stained only in the absence of more active adsorbants, that orthoclase acquires iron stain more readily than quartz, and that while $Al(OH)_3$ is a good adsorbant of iron, pure kaolin will adsorb but little unless activated by some such substance as the alkali carbonates. The iron content of clays up to about 5.0 per cent Fe_2O_3 is shown to be a linear function of the alkali content, the equation

$$A = \frac{10B - 4}{7}$$

where A = percentage of Fe_2O_3 present and B = percentage of $Na_2O + K_2O$ present holds true for averages of several analyses, but not for individual clays, within these limits. It is suggested that the deep red color developed by so many tropical soils is a result of the retention of iron by the hydroxides which occur plentifully in such soils.

It has often been noted that sandstones and clays containing the same percentage of iron as shown by chemical analysis may exhibit totally different colors, and conversely, two different materials with wide variation in iron content may appear of almost exactly the same shade. Even after allowance for differences in degree of oxidation of the iron and for the presence of other coloring agents such as manganese and titanium, a considerable residuum of cases remains in which ferric iron appears to be the sole coloring agent present, and yet where the depth of color bears no apparent relation to the amount of iron present. It is the purpose of this paper to discuss some of the evidence at hand bearing an explanation of these individual differences.

If a given amount of any opaque color be spread in a thin coat over the surface of the separate grains which make up a sandstone then each grain will appear to casual inspection as if it were composed wholly of the coloring matter. Since the surface of a solid figure increases as the square of the radius, while the mass increases as the cube, a given weight of fine-grained material will have a much greater surface area than an equal weight of the same material com-

posed of larger grains. It may be readily shown that the total surface of the one is to the total surface of the other inversely as the average radii of the grains composing them. Since staining is purely a surface effect, a much greater amount of stain would have to be applied to the fine-grained material than to the coarse-grained material in order to bring them to the same shade of color. Thus J. K. Roberts says: "The deep red color of the rock (a sandstone) is due to the peculiar physical condition in which it occurs, namely, as a *thin opaque coat around the sandgrains* and scattered through the matrix. *The percentage of ferric oxide is far less than in most red clays.*"[1] (Italics are mine.) The same point was well brought out by an experiment recorded by Robinson and McCaughey[2], who found that a fine quartz flour containing 2.5 per cent ferric oxide was very closely matched in color by a coarse quartz sand averaging 2 mm. in diameter and containing only 0.25 per cent ferric oxide.

The problem reduces itself, then, to the determination of the condition, or set of conditions, under which the iron present in a residual clay or sandstone will attach itself to the coarser fragments, and the conditions under which it will rather attach itself to the finer portions of the material. In order to determine as far as possible these conditions the following laboratory work was carried out.

A TRIASSIC CONGLOMERATE

The first material studied was a coarse conglomerate, supposedly of Triassic age, and obtained from a natural exposure a few miles north of Chapel Hill, North Carolina. This rock is composed almost wholly of well-rounded pebbles of various types of rock, together with considerable quantities of water-worn quartz grains. The separate fragments are firmly cemented together by a heavy deposit of a hydrous ferric oxide which completely fills the interstices. A fragment of this material was digested for several hours in hot dilute HCl, and at the end of this time the cement was almost completely removed. After filtration the insolubles remaining on the filter were dried and run through a series of sieves (10- to 200-mesh). Almost

[1] "Triassic Basins of Northern Virginia," *Pan-American Geologist*, Vol. LIX (1923), p. 192.

[2] *Bureau of Soils, Bulletin 79* (1911), p. 20.

no material passed the 20-mesh sieve, and none at all was recovered beyond the 100-mesh. Since not only were almost no insolubles obtained from the cement, and since no calcium and but very little silica or alumina were found in the filtrate, it appears that the cementing material, in the case of this conglomerate, was almost pure ferric oxide.

A TRIASSIC SANDSTONE

In deep contrast to this conglomerate is a partially consolidated, chocolate-colored Triassic sandstone, also obtained near Chapel Hill. This sandstone is a portion of the "Newark" beds, and forms the most westerly portion of the Triassic at the point where found. Its color, obviously due to ferric oxide, can be imitated exactly by grinding a mixture of hematite and quartz in an agate mortar. It is rather arkosic, containing considerable quantities of undecomposed and partially decayed feldspars, as well as quartz grains and a clayey cement. There is enough of this latter present so that when thoroughly moistened, especially if a slightly weathered sample be chosen, considerable plasticity is developed. When tested according to a modification of the method adopted by the Bureau of Soils[1] the colloids present were determined as 29.1 per cent of the whole. Of the extracted colloid, 9.65 per cent was determined as Fe_2O_3, while this substance made up but 3.07 per cent of the original sample. There was, therefore, 26.3 per cent of non-ferruginous colloid present. When the poorly cemented sandstone was crushed and rubbed up under water until all of the finer material could be washed out, it was seen that the quartz and feldspar were but slightly stained and formed a great contrast with the heavily coated grains and pebbles in the conglomerate described above. It may be noted that in this sandstone the feldspars showed greater stain than did the quartz.

A RED RESIDUAL SOIL

A red soil resulting from the subaerial decay of granite at Chapel Hill was next studied. When carefully washed and sieved it was found that the quartz grains bore no trace of iron stain, the deep red color of the soil being entirely confined to the clay fraction and to cracks in the larger rock fragments. An analysis of this soil

[1] *U.S. Department of Agriculture, Bulletin 1193* (1924), p. 32.

showed: ferric oxide, 3.65 per cent; total colloids, 41.5 per cent, of which 8.08 per cent was ferric oxide; total non-ferruginous colloids present. 38.1 per cent.

Since the conglomerate in which the coating of iron oxide was cemented so firmly to the surface of each grain contained little or no non-ferruginous colloids, and the red sandstone in which some staining of the sandgrains was visible contained 26.3 per cent of such colloids, and since the residual soil in which totally unstained quartz grains were found contained 38.1 per cent non-ferruginous colloids, the idea at once suggests itself that there is some connection to be traced between colloids and iron stain. In order to trace, if possible, this connection, the following series of experiments was run.

Six mixtures, the basis of each being 20-mesh white quartz, were prepared and placed in evaporating dishes as follows: No. 1, quartz and ferric chloride solution; No. 2, the same, with the addition of aluminum chloride; No. 3, quartz, 20-mesh orthoclase, and ferric chloride; No. 4, the same, with the addition of aluminum chloride; No. 5, quartz, kaolin, and ferric chloride; No. 6, quartz, orthoclase, kaolin, ferric chloride. The amount of ferric chloride added to each was the same. Ammonium hydroxide was next added to precipitate the iron and aluminum, the mixture evaporated to dryness, and heated to dull redness in order to convert the hydroxides to anhydrous oxides and to volatilize the ammonium chloride formed. If the presence of non-ferruginous colloids tended to prevent the iron oxides from adhering to the mineral grains, then the contents of dishes 2, 4, 5, and 6 should exhibit but little iron stain, while the quartz and orthoclase in dishes 1 and 3 should be heavily stained.

In order to determine how much of the iron stain would adhere, the calcined mixtures were placed in shaking-bottles such as are used for the mechanical analysis of soils, and were shaken in distilled water until no more of the ferric oxide could be removed by this method, this point being considered reached when a fresh change of water remained clear after twenty minutes' agitation. After drying, the grains were examined by means of a binocular microscope.

In dishes 1 and 3, which had contained no alumina or kaolin, the quartz and orthoclase had been deeply stained, the color being present in the form of a fairly uniform coating of ferric oxide, dark

red in color. In dish 3 the orthoclase had acquired a deeper stain than had the quartz. In dishes 2 and 4 hardly any ferric oxide had adhered to the grains, but, being adsorbed by the colloidal alumina, had been removed along with it during the washing process. In samples 5 and 6 the quartz and orthoclase had acquired a light orange-yellow stain, the kaolin being evidently a less effective adsorbant for the iron than was the alumina.

An attempt was also made to determine the amount of iron necessary to give quartz an appreciable stain, but this proved so small that accurate results were impossible. Some 20-mesh white quartz was stained as above, using a mixture of the chlorides of iron and aluminum. After thorough agitation in the shaking-bottle the quartz grains were removed and tested for iron. The grains, stained a light but decided orange-yellow, appeared to have adsorbed but little iron, the mean of three analyses giving ferric oxide 0.039 per cent.

ADSORPTION OF IRON BY CLAYS

Similar experiments were carried out for the purpose of determining the adsorption of iron by kaolin. It had been suggested by the results obtained in the previous series of experiments that kaolin was a less active adsorbant than alumina. Another suggestive thing noted was a band of almost pure white kaolin occurring in the red residual soil described above. This kaolin was apparently derived from the weathering of a vein of feldspar which traversed the granite, and contained no appreciable iron except where cut across by minute cracks or joints which permitted the seepage of ground water into the interior of the vein. The face of each crack was stained a bright brownish-yellow, this discoloration extending back into the kaolin for about 1 mm. Qualitative tests showed the presence of considerable iron in these discolored portions of the kaolin, the iron having evidently been brought in by circulating ground waters and adsorbed by the kaolin.

To test the adsorptive power of kaolin a commercial product from Spruce Pine, North Carolina, was used. Weighed amounts of the substance were placed in soil-shaker bottles and solutions of ferric chloride and ferrous sulphate of different strengths added. After a three-hour agitation in the shaker the contents were put through filters. No attempt was made to wash out the iron solutions, but the

wet kaolin was allowed to drain for half an hour on the filters. It was at first intended to determine iron adsorption by colorimetric methods, but since in no case was enough iron adsorbed to produce a red color even after ignition it was considered that this kaolin was incapable of adsorbing iron to any extent, and no further tests were made. It was observed, however, that the weaker iron solutions had been completely decolorized, and only a trace of iron appeared in the filtrates. In spite of the fact that deposition of ferric hydroxide from the ferrous sulphate solutions might have been expected, the ferric chloride was weakened far more rapidly, and when tested, the filtrate showed the presence of considerable soluble aluminum compounds, presumably the chloride. Evidently there had been an exchange of bases, and a portion of the alumina in the kaolin had been replaced by ferric iron and the mineral partially converted into its ferric equivalent, nontronite.[1] Since nontronite is pale yellow in color, and since the original kaolin was cream-colored rather than white, no appreciable change in color might be expected to accompany this alteration.

In further attempts to make the kaolin adsorb iron in quantities sufficient to give it a marked color it was found that the addition of potassium and sodium salts would increase the adsorptive power of the kaolin tremendously. Since residual soils contain considerable quantities of the alkaline carbonates derived from the decay of feldspars it may well be the presence of such salts that enables them to retain the iron and assume various shades of red and yellow. It is well known that soil particles will take up considerable quantities of potassium, magnesium, and sodium salts and retain them tenaciously in spite of their great solubility.[2]

An attempt was therefore made to correlate the percentage of iron and alkali salts found in a series of clays, some slight degree of correlation being expected. To this end a series of about three hundred clay analyses were averaged together in groups of about thirty analyses each, such averaging being expected to do away with accidental and irregular variation.[3] All glacial clays were rejected as far

[1] F. W. Clarke, *Data of Geochemistry*, 5th ed., p. 494; *U.S. Geol. Survey Bull. 770.*

[2] F. W. Clarke. *op. cit.*, p. 212.

[3] Most of these analyses were taken from *Bulletin 35, New York State Museum*, and from Volume XI of the *Missouri Survey.*

as possible, since such clays tend to contain large amounts of undecomposed rock fragments of extreme fineness. The first group contained thirty clays whose iron content varied from 0.0 per cent to

TABLE I

Group	Average Fe_2O_3 (Percentage)	Average K_2O+Na_2O (Percentage)
I	0.53	0.89
II	1.55	1.44
III	2.44	2.09
IV	3.45	2.81
V	4.37	3.36
VI	5.45	3.36
VII	6.47	3.40
VIII	7.50	3.37
IX	8.39	3.21
X	9.32	3.30

1.0 per cent Fe_2O_3, the second thirty clays varying from 1.0 per cent to 2.0 per cent Fe_2O_3, etc., the last group (in which there were but thirteen analyses) ranging from 9 per cent to 10 per cent Fe_2O_3. The

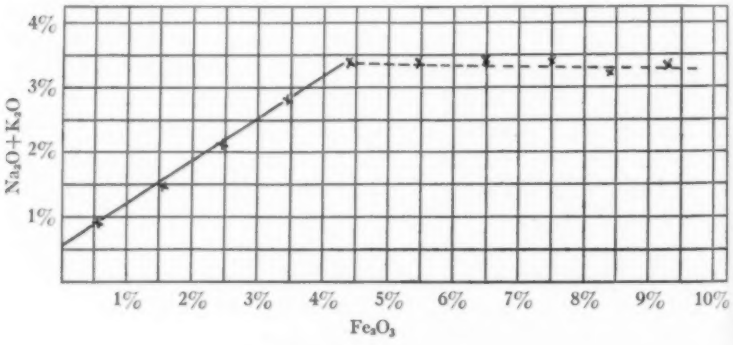

FIG. 1

averages obtained for each group are shown in Table I, and a graphic representation of the iron-alkali relations is given in Figure 1.

IRON AND ALKALI CONTENTS OF CLAYS

It will be seen that in Groups I–V, inclusive, the relation between iron and alkali is almost a linear function, the curve drawn through

the plotted points being as straight a line as could be expected, but that the alkali contents of the succeeding groups are practically a constant. The reason for this abrupt change is not at all clear, but it seems evident that any iron present in excess of 4.5 per cent Fe_2O_3 is not held by alkaline salts, but retained in some other manner. The solid straight line passing through or near the plotted points in Figure 1 has the equation

$$A = \frac{10\,B - 4}{7}$$

where A = percentage of Fe_2O_3 and B = percentage of alkalis. No explanation of the values of the constants involved has been found. A comparison of the actual iron found, and iron as computed from the alkali contents by means of this formula, is given in Table II. Be-

TABLE II

Group	Fe_2O_3 Found (Percentage)	Fe_2O_3 Calculated (Percentage)	Difference
I.....	0.53	0.49	0.04
II.....	1.55	1.50	0.05
III.....	2.44	2.41	0.03
IV.....	3.45	3.44	0.01
V.....	4.37	4.23	0.14
VI.....	5.45	4.23	1.22
Etc.	Etc.	Etc.	Etc.

yond Group V the percentage of alkalis remains practically constant at 3.30±0.1 per cent (see Table I), so that the equation noted above breaks down completely at this point. Until 4.50 per cent Fe_2O_3 is reached there is, however, a very remarkable agreement. This equation is purely an empirical one, derived from observational data, and, as has been said, no meaning has as yet been read into the constants which appear in it.

It would appear from the results of the experiments described above that there are two chief factors governing the intensity of color in sandstones and clays. First, the distribution of the coloring matter, whether adhering to the grains or adsorbed by the matrix; and second, the actual content of iron oxide. The former seems to be governed, at least in part, by the amount of non-ferruginous colloid present, such colloids tending to prevent adherence of the iron to

the mineral grains. One factor governing the actual iron content up to a point where more than enough iron is present to secure a decided color appears to be the alkali content, the iron increasing with the alkalis up to a certain point. This relation between iron and alkalis is not apparent when individual analyses are taken, but immediately appears when averages of several analyses of material of approximately the same iron content are employed. It should be noted, however, that merely a high iron content does not in itself mean a deep color, although such color is impossible without it.

It also appears that quartz sand segregated from residual soils rich in colloids should be free from iron stain, but on the other hand colloid-free aggregations should be peculiarly susceptible to the acquisition of such stain. Since feldspar shows a decided tendency to acquire a deeper stain than quartz when subject to the same conditions, it appears that a deep coloration should be met with more often in arkosic than in non-arkosic sandstones. This may, in part at least, account for the intense color met with in many of the arkosic sandstones of the eastern Triassic.

The experiments dealing with adsorption of iron by kaolin show that this mineral is only an active adsorbant when it carries such substances as the alkali carbonates, but that other colloidal aluminous compounds, as $Al(OH)_3$, need no such activating substances. Since in tropical and subtropical climates the processes of rock decay are often carried farther than in the more temperate climates and the residual soils are much richer in hydroxides[1] we have here a possible explanation of the development of intense red coloration and laterization so typical of such tropical regions. The hydroxide-rich residual soils are able to retain the ferric compounds derived from the decay of the iron-bearing minerals, while in more northern regions the hydroxide-poor and silicate-rich soils are unable to retain such compounds, and the iron is rapidly leached out. Unfortunately, the exact climatic factors leading to a high development of hydroxides in residual soils have not been accurately determined, there being a great diversity of opinion on this point. Further experimentation along these lines is being undertaken by the author, and it is hoped that more decisive results may be forthcoming in the near future.

[1] F. W. Clarke, *op. cit.*, p. 496.

INTRAFORMATIONAL PHOSPHATE PEBBLES OF THE TWIN CITY ORDOVICIAN[1]

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ABSTRACT

The results of a study of numerous, black polished grains and pebbles of calcium phosphate occurring along "corrosion zones" in limestones are here set forth. The material is described in respect to its field occurrence and associations and its physical and chemical characteristics.

The evidence indicates that the pebbles have been formed as a result of solution of the lime carbonate with its contained phosphate under anaerobic conditions with subsequent deposition of the phosphate on the interior of minute shells forming internal molds and granules. This conclusion suggests a source of phosphorus, a manner of accumulation for phosphate layers in limestones, and also that thin layers of phosphate pebbles indicate disconformities due to non-deposition and marine solution.

INTRODUCTION

A study of certain scattering black phosphatic pebbles occurring in limy sediments in the Minneapolis–St. Paul region was made to determine, if possible, their field associations and relations, their physical and chemical characteristics, and their origin. They bear marked resemblances to material collected from phosphate beds elsewhere, and hence may throw some light on the still obscure problem of the formation and geologic relations of phosphates in general.

The writer is indebted to Professors Grout and Stauffer of the University of Minnesota for suggestions and encouragement in this work. The excellent works of Murray and Renard and the *Data of Geochemistry* by F. W. Clarke have been freely drawn upon for information.

FIELD OCCURRENCES

Black phosphate pebbles are found in the region of the Twin Cities at certain horizons in the Mohawkian (Galena) Series. Specifically these are: (1) a transition zone at the top of the St. Peter sandstone and the base of the Platteville limestone, (2) the

[1] Rewritten from thesis presented in partial fulfilment of the requirements for the degree of Master of Arts, University of Minnesota.

middle Platteville at the top of the "Buff limestone" and base of the "Bellerophon bed,"[1] (3) at the top of the Platteville limestone and base of the Decorah shale, and (4) at the top of the Decorah shale and base of the Galena dolomite. The first-mentioned horizon was the only one that yielded pebbles in any quantity. Only a very few black polished grains were observed at the Decorah-Platteville contact. The other two horizons yielded small amounts of the same.

The first and most important phosphate pebble zone lies at the top of the few feet of shales that separate the St. Peter sandstone and the Platteville limestone and are now assigned to the Platteville.[2] Excepting minor variations, this zone is much the same in all parts of the Twin City region. A typical section is given below:

	Feet	Inches
Platteville limestone	-	-
Pebble bed (siliceous dolomite)	1	0
Transition zone		
Green to blue shale	2	4
Hard sandy calcareous layer	0	4
Green shale or clay	1	2
St. Peter sandstone		
Uppermost "spotted" and consolidated beds	-	-

The foregoing section is exposed in an excavation at Winifred and South Wabasha streets, St. Paul. It is from here that pebbles and matrix were taken for the analyses. The upper St. Peter is "spotted" and intermixed with shale possibly due to reworking by the sea.[3]

The pebbles are characterized by certain associations, such as the following:

The bed containing the pebbles is a ten- or twelve-inch buff, fine-grained siliceous dolomite or dolomitic limestone (see analysis *B*). It rests with very sharp and slightly irregular contact on green limy shale. The pebbles are chiefly concentrated in the first few inches but a few are scattered through the uppermost part of the shale. Both of these beds are nearly unfossiliferous, except as later mentioned.

[1] F. W. Sardeson, "Intraformational Conglomerates in the Galena Series," *Amer. Geologist*, Vol. XXII (1898). Plate IX. The classification used here follows this article in the main.

[2] C. R. Stauffer, "Mineralization of the Platteville-Decorah Contact Zone in the Twin City Region." Paper presented before the Geological Society of America, 1925.

[3] C. R. Stauffer, *op. cit.*

A few large cavities in the dolomite may represent open spaces left by the solution of fossils. The matrix is nearly everywhere predominant and the pebbles occur as scattered grains or small aggregates in this bed. The aggregates are usually intermixed with much ferruginous matter evidently derived from the oxidation of pyrite.

Perhaps the most significant feature of these pebble zones is their association with large irregular flat limestone pebbles and "corrosion surfaces." The limestone pieces occupy much of the first three inches in the lowest pebble zone. They are composed of a dense fine-grained bluish limestone. They vary from an inch to several inches in thickness and from an inch to over twelve inches in length. Their boundaries are marked by a thin layer of pyrite or a dark stain (probably finely divided pyrite) that diminishes within. Otherwise they are rendered visible by their bluish color which is contrasted with the buff dolomite matrix. The slabs are quite similar to the large "corrosion pebbles" described by F. W. Sardeson.[1] The black phosphatic pebbles are most abundant on and between these larger slabs. The latter occurrence gives rise to aggregates.

All of the other pebble layers are associated with what has been termed a "corrosion surface" or "zone."[2] These surfaces are irregular, blackened contacts between different beds. Their blackness is due to a stain of finely divided pyrite and a trace of manganese.[3] This stain diminishes downward, but never upward, for it is overlain by a fresh, unblackened deposit of lime-magnesium carbonate. In places, great irregularities of this surface give rise to detached pieces which resemble in appearance the larger slabs seen at the lowest pebble zone. The corrosion surface at the top of the Platteville has been interpreted as a minor disconformity[4] and it is probable that the others must be so considered. They do occur (with the possible exception of the lowest) at the division planes of faunal zones.

The phosphatic pebbles associated with the lowest corrosion surfaces are described by Sardeson as "numerous small black pebbles and coarse quartz grains associated with or in large fucoidal casts." The pebbles and corrosion surfaces are interpreted as being due to "resorbtion" which

[1] F. W. Sardeson, *op. cit.*, p. 319.
[2] F. W. Sardeson, *op. cit.*, pp. 317–18.
[3] C. R. Stauffer, *op. cit.*
[4] C. R. Stauffer, *op. cit.*

left the surface irregular and the top of the stratum saturated with oxide of iron and manganese. Extreme irregularities of the surface may have given rise to loose, isolated, blackened pebbles, or the same may be parts of a broken up stratum or lamina, reduced by absorbtion like the ground surface.[1]

In a later article the phosphate pebbles are spoken of as "small, blackened irregularly shaped pebbles associated with the corrosion surface so that their origin as loosened corroded fragments is not far to seek."[2]

F. F. Grout has said that phosphatic pebbles occur at the base of the Platteville in southwestern Wisconsin.[3] A collection of these specimens was examined by the writer and was found to be similar in nearly all respects to that of the Twin City region. H. F. Bain describes "numerous small rounded black, pebble-like bodies" composed of phosphate of lime from the very base of the Galena in the Upper Mississippi Valley zinc-lead region.[4] Similar conglomerates of phosphatic and chert pebbles associated with diminutive fossils, chiefly mollusks, have been noted at the base of the Maquoketa shale and top of the Galena beds in the same region by A. C. Trowbridge and E. W. Shaw,[5] U. S. Grant,[6] and H. S. Ladd.[7]

PHYSICAL CHARACTERISTICS

MACROSCOPIC CHARACTERISTICS

The typical pebbles are black and opaque. A very few are some shade of brown or of a lighter color. They vary widely in size, from a fraction of a millimeter up to an extreme of thirteen millimeters (Figs. 1 and 2). The average diameter is small in many cases—often less than a millimeter—so that the term "pebble" is, therefore,

[1] F. W. Sardeson, *op. cit.*, pp. 317–18.

[2] F. W. Sardeson, "Characteristics of a Corrosion Conglomerate," *Bull. Geol. Soc. America*, Vol. XXV (1914), p. 269.

[3] F. F. Grout, oral communication.

[4] H. F. Bain, "Zinc and Lead Deposits of the Upper Mississippi Valley," *U.S. Geological Survey, Bull. No. 294* (1906), p. 25.

[5] A. C. Trowbridge and E. W. Shaw, "Geology and Geography of the Galena and Elizabeth Quadrangles," *Ill. State Geological Survey, Bull. No. 26* (1916), pp. 67–68.

[6] U. S. Grant and E. F. Burchard, "Geologic Atlas of the United States," *Lancaster-Mineral Point Folio, No. 145, U.S. Geological Survey* (1907), pp. 7–8.

[7] H. S. Ladd, graduate student, State University of Iowa. Personal communication, 1925.

hardly applicable to much of the material. The grains vary in weight up to a maximum of 1.3 grams.

A great diversity of shape is characteristic. In addition to numerous globular, lenticular, and subangular flat pieces there are

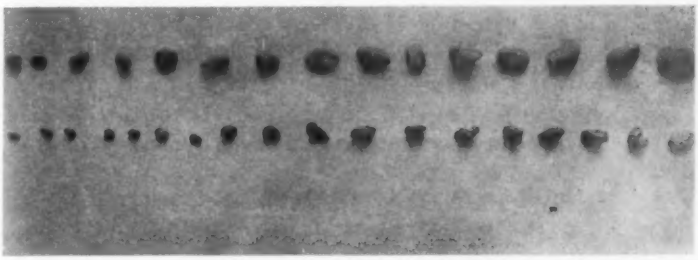

FIG. 1.—Phosphate pebbles from basal Platteville limestone, St. Paul, Minnesota. About natural size.

numerous fossil forms. These have the same external color and polish as the rest of the material and differ only in shape. Of the collections examined they constituted from 15 to 40 per cent of the

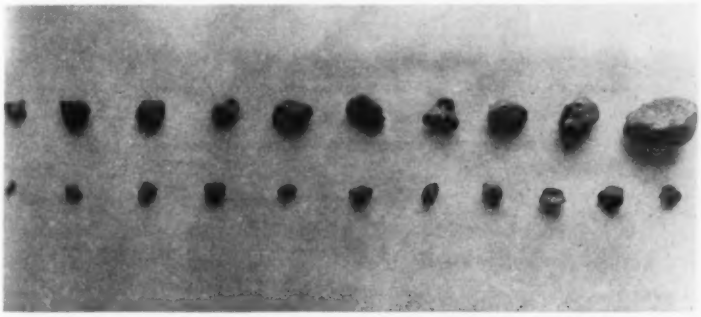

FIG. 2.—Phosphate pebbles from basal Platteville limestone, southwestern Wisconsin. About natural size.

specimens. Many of the flat pieces may be fossils altered beyond recognition. In greatest abundance is a diminutive or undeveloped genus of gastropod. The largest of these forms was only 8 millimeters high and the largest whorl had a diameter of 4 millimeters. The usual

form is much smaller. The fragmental character and the fact that, in so far as observed, the forms are all "interior casts" or molds makes them difficult of identification. Only a very few other fossil forms are present. These include a few bryozoans, a number of small, flat fragments bearing concentric ridges (probably bivalve shell fragments), a single interior mold of a very minute pelecypod, and a trilobite pygidium. The only unaltered fossils were several minute linguloid forms.

A noteworthy feature of these pebbles is their highly polished surface. Most of the grains are smooth and have this varnish or glaze. A few, however, are dull.

The interior is usually structureless and dull. It is fine grained and is occasionally lighter than the exterior. Fine crystals of pyrite are abundant in many specimens. In several instances a very small, dark brown or black shiny linguloid brachiopod was observed in the interior. A gastropod interior mold seems to have formed a nucleus for one pebble.

The pebbles appear to lose their black color and become gray or white on weathering. The matrix in this case turns yellow or red, due presumably to the oxidation of pyrite.

The unaltered material has a hardness of about 5 and breaks with an uneven fracture. That collected had a specific gravity of about 2.66–2.68. The powdered grains yield water in the closed tube and impart a yellow color (probably due to iron) to the borax bead. Fragments fuse with great difficulty on the edge.

MICROSCOPIC FEATURES

Thin and polished sections were examined. An amorphous black and amber colored mineral, probably an impure variety of collophane, is most prominent in the pebble-like bodies. The matrix is a dull gray or yellowish mass of fine crystals—some of which are well-defined rhombs of dolomite. The yellow is due in part to limonite derived from the large amount of pyrite present and possibly also to phosphatic or organic matter.

The collophane is often opaque except in a very finely powdered state. This seems to be due to the presence of iron sulphide in a state of very fine division—possibly it is amorphous. The very light

amber or yellow bodies may be chitin. The great diversity of shapes is a marked feature of the thin sections as well as of the hand specimens. The material is all amorphous. A few of the chitinous fragments exhibit a weak birefringence and are extinct when the structure lines are parallel to the plane of vibration of the microscope. The material collected had an index of refraction of $1.563 \pm .022$.

Of the inclusions, pyrite is most abundant. Many tattered aggregates, specks, and "needles" and "crescents" of this mineral were observed. The curved areas probably represent replaced organic fragments. Quartz was seen to have the same relations to a much less degree. The extension of the inclusions to the edge, or nearly to the edge, suggested the absence of a shell on the fossil forms.

A few of the pebbles were made up of lighter colored globular masses agglutinized into a single mass. The outlines of the mass seemed to conform to the individual globules rather than cut across them. Some pebbles presented a light interior with a black opaque rim. Concentric structure was observed in only one case, and in this specimen may have been due to weathering.

The matrix is chiefly dolomite and calcite. The former is present in well-defined rhombs. In small amounts are pyrite, kaolinite, and quartz grains. The quartz grains are comparatively rare; those found are for the most part well rounded and some have pitted and frosted surfaces.

DISCUSSION OF ANALYSES

A comparison of the pebbles and their matrix reveals marked differences. The pebbles are essentially phosphate of calcium with inclusions of iron sulphide, calcium carbonate, and silica. The matrix is a calcium-magnesium carbonate with some silica and alumina. Nearly all of the phosphorus of the rock is in the form of pebbles. The pebbles likewise contain most of the iron sulphide. The manganese content of the pebbles is considerably less than that of the matrix. F. F. Grout found the reverse to be true of the Wisconsin pebbles and matrix. He found .106 per cent MnO_2 in the matrix and .190 per cent MnO_2 in the pebbles. His analysis, however, also demonstrates the insoluble character of the matrix as shown by the high percentage (43.9) of insoluble material.

A comparison of an analysis of phosphate nodules recently

dredged up from the sea bottom shows considerable resemblance to the pebbles here analyzed. The modern nodules are relatively impure as they contain more silica and carbon dioxide than do the Ordovician specimens.

Mineralogically the calcium phosphate is probably present as a very impure variety of collophanite.

CHEMICAL CHARACTERISTICS

TABLE OF ANALYSES

	A	*B*	*C*
SiO_2	3.46	18.59	11.70
Al_2O_3	*	6.74	4.11
Fe_2O_3 / FeO	6.78	4.65	3.75
MgO	.43	11.64	.84
CaO	42.98	22.10	40.96
H_2O+	1.47	1.69	3.65†
H_2O-	.52	.35	.....
CO_2	3.37	27.64	10.64
TiO_2	.26	.25	.....
P_2O_5	30.91	1.43	23.54
SO_3 / S	.19 / 3.48	.78‡	1.39
MnO	.07	.28	.....
Total	93.92	97.14	100.18

* Not determined. † "Ignition." ‡Calculated as sulphide sulphur.

A = Black pebbles from basal Platteville limestone. Winifred and South Wabasha streets, St. Paul, Minnesota. F. J. Pettijohn, analyst.

B = Matrix from same sample as A. F. J. Pettijohn analyst.

C = Phosphate concretions from sea bottom at 1,900 fathoms. "Deep Sea Deposits," *Challenger Reports*, p. 452. Recalculated from separate analyses of soluble and insoluble portions. C. Klement, analyst.

Analyses A and B made in the laboratory of the Geological Survey of Minnesota by courtesy of Dr. W. H. Emmons.

ORIGIN OF THE PHOSPHATE PEBBLES

It is thought that preceding the deposition of the phosphate pebbles, normal deposition of limy sediment was going on. This in time would have formed an ordinary marine limestone. Included in this deposit were the ordinary organic remains containing small amounts of phosphorus as well as those unusually high in this element, as the lingulas. The phosphorus was thus extracted from sea water in the usual way. Land sediments were essentially absent, owing presumably to distant or low lying lands.

Deposition then stopped. The reason for this is not clear. Pos-

sibly hydrogen sulphide was formed in sufficient amounts by reducing bacteria to contaminate the waters and thus prevent the lime secreting forms from flourishing.[1] That conditions became unfavorable is shown by the diminutive fossil forms present, the predominance of one species over the usual fauna, and non-deposition of lime.

Non-deposition was followed by partial solution of the deposit previously laid down. It is a well-known fact that sea water under ordinary conditions is not saturated with carbonate of lime and will, therefore, to some extent redissolve the limy oozes and shells—as etched shells indicate. This redissolving, however, is very slow as has been shown experimentally.[2] The presence of free carbonic acid hastens the process materially. Carbon dioxide may, then, have been present in quantity. The evidence for solution is a marked feature of these phosphate zones. It is given here: (1) The absence of calcareous shells. (2) The presence of only a few relatively insoluble shells such as were originally formed of lime phosphate—as the lingulas. (3) The abundance of numerous small interior molds which imply the removal of the shell. (4) A few rounded quartz grains which because of their frosted surfaces are suggestive of a wind-blown origin may be those left behind from the solution of a considerable deposit. (5) Associated insoluble material as a siliceous dolomite (dolomite is said to be formed in some cases by the removal of the more soluble lime carbonate by the sea water).[3] (6) Manganese and pyrite stain of the matrix and the outer parts of the corrosion pebbles are indicative of non-deposition. The manganese may be a residuum of a larger deposit. (7) The irregularities of a corrosion surface of the limestone appear to indicate solution. (8) Rounded, irregular corroded limestone pebbles which represent undissolved pieces of the original lime deposit.

It seems probable that much of the phosphorus in the original bed was dissolved, inasmuch as there is no residual accumulation of

[1] C. R. Stauffer, *op. cit.* The suggestion is here made that such a cause may explain the failure of deposition marking the contact between the Platteville and Decorah.

[2] A. G. Mayer, "Submarine Solution of Limestone in Relation to the Murray-Agassiz Theory of Coral Atolls," *Proc. Nat. Acad. Sci.*, Vol. II (1916), pp. 28–30.

[3] F. W. Clarke, "Data of Geochemistry," *U.S. Geological Survey, Bull. No. 695*, p. 566.

phosphorus other than a few linguloid shells. That phosphate is soluble in carbonated waters has been shown by Murray and Renard, who noted the absence of the bones of vertebrates on the sea floor and the etched condition of sharks' teeth and similar dense phosphatic matter.

The phosphoric acid thus dissolved and the phosphorus already present in traces in sea water were then precipitated on the interior of small marine univalve shells. Possibly this was due to organic matter present in such places, which acted as a precipitant, and also in part due to the ammonia generated by the decay of the same. Andreé has suggested the following reaction:

$$2\ (NH_4)_3PO_4 + 3\ CaCO_3 = Ca_3(PO_4)_2 + 3\ (NH_4)_2CO_3.$$[1]

The subsequent removal of the shells by solution left interior molds which are now to be found in great numbers. A small amount of phosphate seems to have been attracted to similar material—such as the lingula shells—and thus gave rise to a granule or pebble. The structureless pebbles may be due to deposition around phosphatic interior molds. Good evidence is lacking for a direct precipitation or replacement of shells and organic forms. A possible exception is the peculiar internal structure that some pebbles show. The peculiar agglomeration of globules appears without any adequate explanation.

As thus outlined the deposition is of a marine intraformational character. This is further confirmed by the widespread nature of these zones, the restriction vertically to rather thin bands, the fossil interior molds, and the associated beds of dolomite and limestone of marine origin. The intraformational nature of these pebbles is further attested by the limy matrix (pebbles in limestone or dolomite are not to be expected from external sources); the absence of any detrital material of similar size, excepting a few quartz grains which may possibly be assigned to wind transportation; the high polish of the material, while occasionally developed by water action, is not the rule for material so worn or transported; the angularity of many of the fragments is not to be expected of water-worn material, and the abundance of interior molds of gastropods nearly precludes the

[1] K. Andreé, "Geologie des Meeresboden," Vol. II (1920), p. 255. Leipzig.

possibility of an external source. The glaze or polish is attributed to the hard, fine-grained amorphous character of the material. The polish so commonly found on phosphate pebbles in general, and the fact that it is found in some cases where movement and attrition seem highly improbable—especially on the nodules of the present deep sea—leads to the conclusion that the glaze or polish is an inherent property of the phosphate precipitated under some conditions. Hayes and Ulrich, however, have attributed the polish of the phosphate grains of the Ordovician phosphates of Tennessee to "rolling around" by wave and tidal action.[1]

Calcium carbonate and iron sulphide (probably amorphous) were precipitated simultaneously with the phosphate. The sulphide in a finely divided state appears to be the black coloring matter, as is suggested by the high sulphur content (3.46 per cent), the pyrite or marcasite crystals visible in the thin and polished sections, and the yellow, rusty appearance of the pebbles developed after long weathering. Carbonaceous matter may also be present as a pigment.

The conditions under which phosphates in general are formed are said to be anaerobic.[2] This seems to have been true of the pebbles here studied. Evidence for the same lies in the following: (1) The presence of ferrous iron (as the sulphide). Both the sulphide and ferrous iron are products of reducing or anaerobic conditions. It is even possible that anaerobic bacteria have brought about the reduction of the sulphates and the formation of the sulphide (as H_2S). This has been observed in the Black Sea[3] and has been suggested to account for the pyrite at the corrosion surface between the Platteville and Decorah formations.[4] (2) Dolomite is said to form under reducing conditions[5] and may, therefore, indicate anaerobic reduction. (3) The fact that normal aerated waters gradually dissolve the

[1] C. W. Hayes and E. O. Ulrich, "Geologic Atlas of the United States," *Columbia Folio, U.S. Geological Survey, No. 95* (1903), p. 6.

[2] Eliot Blackwelder, "The Geologic Rôle of Phosphorus," *Amer. Jour. Sci.* (4), Vol. XLII (1916), pp. 292–93.

[3] N. Androussof, "Guide des Excursions du VII Cong. Geol. Internat," No. 29 (1897), p. 6. Reference not examined.

[4] C. R. Stauffer, *op. cit.*

[5] Edward Steidtman, "The Origin of Dolomite as Disclosed by Stains and Other Methods," *Bull. Geol. Soc. America*, Vol. XXVIII (1917), p. 447.

phosphate of bones, teeth, and shells[1] suggests that unusual conditions—possibly anaerobic—must have prevailed.

Specific evidence indicating the source of the phosphate is lacking. The nearly universal presence of the element in living organisms, especially certain brachiopods and crustaceans and its rarity elsewhere indicate an organic source. The presence of lingulas which construct shells of phosphate suggests or confirms this hypothesis. Phosphoric acid is much more abundant in the limy sediments on the sea bottom and in limestones than it is in sea water, hence these materials furnish a more plausible source of the phosphorus. This element is, of course, combined in the hard parts of organisms in these deposits. Unless we assume, therefore, that the P_2O_5 content of the ocean water was radically higher than that of the present day, the phosphate in the lime deposits furnishes the only source worthy of consideration. Geologists have explained the superabundance of phosphorus at times by a wholesale killing of life-forms. This assumption is for the most part without evidence. Solution is, therefore, believed to make considerable phosphorus available.

The resumption of normal deposition of calcium carbonate is believed to have followed a return to normal conditions of sedimentation.

A summary of the history of formation is:

1. Deposition of calcium carbonate by organisms in the usual manner with subordinate amounts of phosphatic matter, silica, kaolin, and other impurities.

2. Cessation of deposition followed by solution of much of the carbonate deposited leaving behind a residuum of insoluble material. Small amounts of phosphate may have been left behind, but larger quantities seem to have been dissolved.

3. Precipitation of much phosphate on the interior of small univalve shells together with small amounts of calcium carbonate and iron sulphide. Also there was some deposition around centers of phosphate such as the linguloid brachiopods and interior molds.

4. The resumption of the normal deposition of lime carbonate followed.

[1] Eliot Blackwelder, *op. cit.*, p. 291.

SUMMARY AND RELATIONS TO WORLD PHOSPHATES

The study of the phosphate zones has led to four conclusions that may have applications in the solution of the puzzling question of the world's marine bedded phosphates. These are:

1. Evidence of marine corrosion or solution suggests a possible source for much of the phosphorus—namely, the dissolved deposit—and a mode of accumulation or concentration by solution of the lime carbonate.

2. The abundance of phosphatic interior molds of univalve shells suggests an origin in a manner similar to that of glauconite, i.e., precipitation of phosphate on the interior of shells by the organic matter present.

3. The prevailing conditions seem to be anaerobic. The black color—due to an abundance of ferrous sulphide (now as pyrite)—is thus explained.

4. These pebbles indicate disconformities due to non-deposition and solution. That these zones are in nearly all cases at the division planes of formations and faunal units is in accord with this conclusion.

REVIEWS

THE STUDIES OF CLOOS ON THE TECTONIC FEATURES OF GRANITE MASSIFS[1]

1. *Geologie der Schollen in schlesischen Tiefengesteinen.* By H. CLOOS.[2] "Abhandlungen der Preussischen Geologischen Landesanstalt," Heft 81 (1920), 123 pp.
2. *Der Mechanismus tiefvulkanischer Vorgänge.* By H. CLOOS. "Sammlung Vieweg," Heft 57 (1921), 95 pp.
3. *Der Gebirgsbau Schlesiens und die Stellung seiner Bodenschätze.* By H. CLOOS. Berlin: Gebrüder Borntträger, 1922, 107 pp.
4. *Tektonik und Magma.* Band I and II. By H. CLOOS AND OTHERS. "Abhandlungen der Preussischen Geologischen Landesanstalt, Neue Folge," Heft 89 and 96, 1922 and 1924. Various expository and descriptive articles by different investigators.
5. *Das Batholithenproblem.* By H. CLOOS. "Fortschritte der Geologie und Palaeontologie," Heft 1. Berlin: Gebrüder Borntträger, 1923, 80 pp.
6. *Einführung in die tektonische Behandlung magmatischer Erscheinungen (Granittektonik).* Part I, *Das Riesengebirge in Schlesien.* By H. CLOOS. Berlin: Gebrüder Borntträger, 1925, 194 pp.

One of the outstanding developments in geology within the last six years has been a very detailed examination of the Silesian granite batholiths, the results of which Professor Cloos of Breslau and those associated with him have contributed in the cited publications. The chief contribution to geological science is the demonstration of the great importance which a minute and thoroughgoing examination of the primary features of a batholith may have in determining the nature, direction, and cause of

[1] The reviewer is especially indebted to Dr. Robert Balk, who has been closely associated with Professor Cloos in his investigations, and who is now carrying forward this work in the United States. He has very generously offered many suggestions and much helpful criticism to aid in the preparation of this review.

[2] Of the foregoing references, those dealing mostly with an explanation of methods, are (1) "Allgemeiner Teil," pp. 84–121; (2) (3) "Methodisches," pp. 5–11; (4) Band II, Parts I, VI, and VII; and (5) "Second Part," pp. 52–72. The balance of these publications, together with (6), deal largely with detailed descriptions of particular intrusive bodies.

magmatic movements. Thousands of measurements have been made on such intrusive bodies as the Lausitz, Riesengebirge, Striegau, and Strehlen granites, and the critical data for such primary features as foliation, schlieren, inclusions, joints, elongation, and slickensides have been assembled in a series of detailed areal maps attending the publications noted, from which theoretical interpretations have been almost entirely eliminated. Those who wish to differ from the authors in the matter of interpretation will find in these maps most of the available data (Fig. 1).

The stretching.—One of the important results of these studies is the discovery and naming of a new primary structure in intrusive masses. This feature is the linear elongation in magmas, and is made manifest by the consistent parallelism of mineral grains such as feldspars and mica. Many investigators have previously noticed parallelism of grain in igneous rocks, but Cloos is the first to demonstrate that it is often so consistently parallel over broad areas. It is called the "stretching" (*Streckung*). In certain of the masses studied this stretching exhibits a horizontal direction which is quite uniform and which varies only a few degrees throughout the entire intrusion. The horizontal projection of the stretching shows everywhere approximately the same strike. The accompanying map (Fig. 1) shows the direction of stretching in the principal batholiths of Silesia. Attention is especially directed to the almost constant direction which it takes in the Riesengebirge, Striegau-Zobten, and Strehlen-Friedeberg massifs. While the direction of the horizontal projection of the stretching is nearly constant in any one of these bodies, the amount of the pitch of this linear structure may vary somewhat more. In general the pitch is not far from horizontal, except at the very contact with the country rock where it often swings into parallelism with the bounding wall against which the liquid magma moved. The simplest cases and those showing the most uniform orientation of the stretching are those named above. The Lausitz granite body, on the other hand, while exhibiting this feature, shows it as a pronounced curve involving a change of direction of more than 90°. In all of these cases the strike of the stretching is discordant with the wall-rock contact, and does not parallel the boundary as one might expect in primary features if they were largely influenced by convection currents, or by strictly magmatic forces.

The foregoing bodies, in which the stretching is so pronouncedly discordant with the boundaries and also with the structure of the wall rock, stand in marked contrast with another series of older intrusive bodies in the north-south Silesian zone and elsewhere. These bodies are structur-

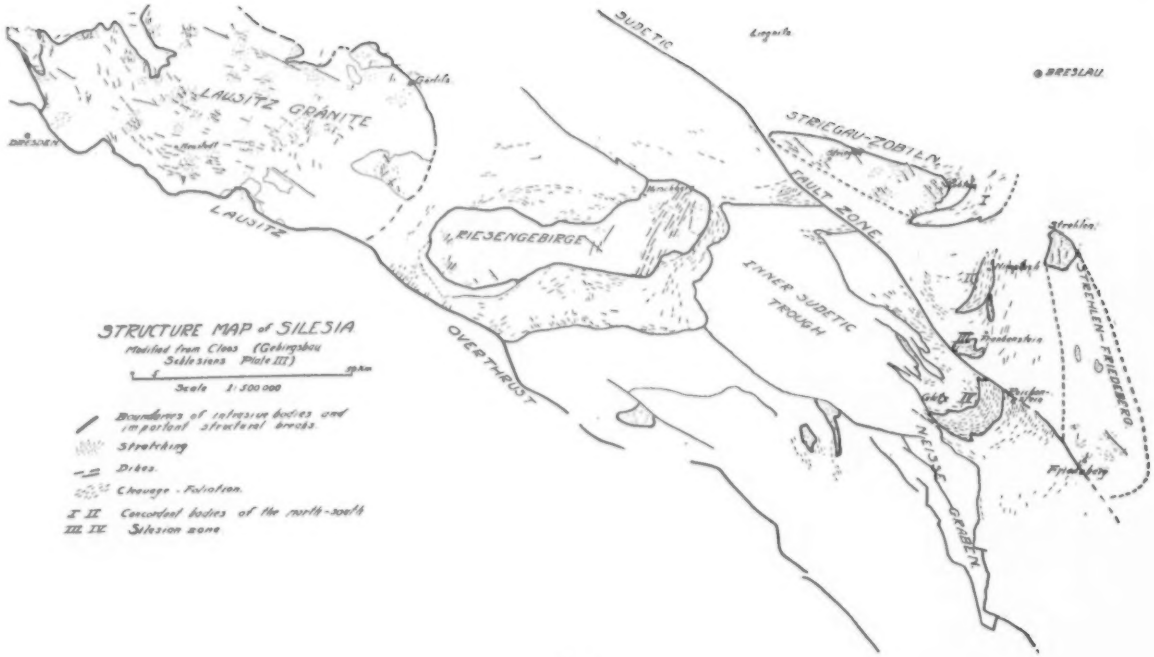
SUDETIC
Liegnitz
BRESLAU
LAUSITZ GRANITE
Görlitz
DRESDEN
Bautzen
STRIEGAU-ZOBTEN
FAULT ZONE
LAUSITZ
RIESENGEBIRGE
Strehlen
INNER SUDETIC TROUGH
STREHLEN-FRIEDEBERG
OVERTHRUST
NEISSE GRABEN
STRUCTURE MAP of SILESIA
Modified from Cloos (Gebirgsbau Schlesiens Plate III)
Scale 1:500 000
Boundaries of intrusive bodies and important structural breaks.
Stretching
Dikes.
Cleavage - Foliation.
I II Concordant bodies of the north-south
III IV Silesian zone

FIG. 1

ally concordant with the structure of the wall-rock, the strike of the stretching being parallel to the strike of the foliation in the containing gneisses and schists. The author concludes that concordant intrusives, such as the small, sickle-shaped bodies of the north-south zone, were subjected to greater pressure or otherwise brought into more intimate contact and closer relations with the wall-rock than the larger discordant bodies of the Riesengebirge, Lausitz, etc. The parts of the concordant bodies now visible may have been brought to their present relations deeper within the crust than the present exposures of discordant bodies; or

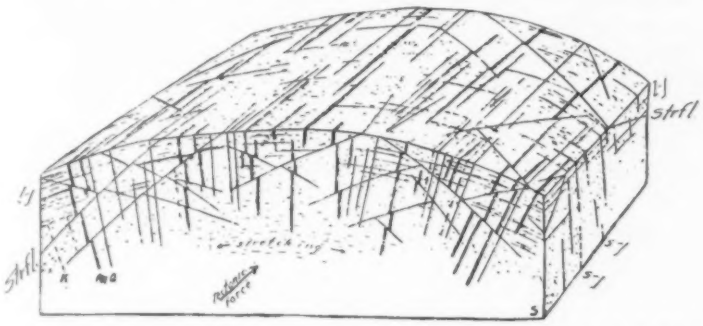

FIG. 2.—Stereogram representing the tectonic features of granite batholiths. (After Cloos.)

O—cross-joints
A–g—cross-joint with aplite
Strfl.—Streckflächen
l–j—l (lager) joints
s–j—s-joints

they may have been intruded during a period of greater tectonic stresses. Whatever the cause of this difference, the two kinds of intrusive bodies are of strikingly different types. While the stretching in the concordant bodies bends in parallelism with the walls, that of the discordant bodies is sufficiently independent of the walls to indicate that tectonic pressure was responsible for its formation. The author concludes that this pressure was applied at right angles to the direction of the stretching and was sufficiently vigorous to obliterate much of the effect of intrinsic magmatic forces and to impress the plastic mass with a linear structure at right angles to its direction of application.

Figure 2, which is copied from the author's publications, is a diagrammatic block of granite from a typical discordant mass. The tectonic force in this case is applied from front to back as indicated by the arrow, and

the plastic deformation of the mass (the maximum elongation) took place at right angles to this direction and is indicated by the fine broken lines crossing from left to right. Flowage in these discordant masses as well as in the concordant ones took place, of course, in other directions than the stretching; the maximum amount of flow, however, must have been in this direction and was sufficiently vigorous to destroy evidences of flow in other directions except immediately adjacent to the wall-rocks.

There can be no doubt that the stretching is truly a primary feature and not an effect of later metamorphism. One of the most cogent proofs of its primary nature is the fact that it is universally confined to the plane of the "lager-joints"—that is to say, to the plane of the foliation, since this is usually parallel to the "*l*-joints." Then, too, the longest axes of wall-rock inclusions are parallel to the stretching also, regardless of the direction of foliation or bedding within these inclusions.

Joints.—Systematic platting of the dip and strike of joint planes has shown the existence of several systems of joints, each having a definite relation to the stretching. As Figure 2 shows, there is one system of joints which, in this generalized diagram, stands vertically and strikes parallel to the stretching. These are called the "*s*-joints." Another system (the "*l*" or "lager-joints") is essentially horizontal and bends with the stretching, so that planes of this system always include the linear structure. The intersection of the "*s*-joints" with the "*l*-joints" then is the direction of stretching. Another very prominent system of joints has been discovered striking at right angles to the stretching, standing vertically where the stretching is horizontal and (where this departs from horizontality) dipping in the opposite direction from the pitch, with the complementary angle to the pitch angle. These "cross-joints" are called by Cloos "*Q*-joints" (*Quer-Klüfte*). It is also noteworthy that the great preponderance of aplite dikes and quartz veins are parallel to these cross-joints, and also stand vertically or dip steeply at right angles to the direction of the stretching. From this evidence the conclusion is drawn that the cross-joints, being in the direction of tectonic stress and at right angles to the stretching, were able to stand open or gap more than the other joint systems and hence were favorable openings for the intrusion of the granite juices. On the other hand, joints extending at right angles to the direction of compression would be closed by this pressure, if indeed they were ever open, and were not easily penetrated. This is definite evidence that the *Q*- or cross-joints are very old and were probably formed immediately upon solidification of the magma.

In quarries the direction of cleavage, parting, "rift," or "grain"

(*Teilbarkeit*) is generally the direction of the *s*-joints, and occasionally that of the *l*-joints if these happen to be steeper than the former. The rough surfaces at right angles to these are the cross-joints (*Q* or *Unspalte—K*). The *l*-joints commonly are parallel to the schlieren and foliation, and though they are often flat lying, they are not to be confused with the bedding, or "lift" (*Bankung*) which is secondary in origin and commonly parallel to surfaces of erosion.

Yet another system is a diagonal series called *Streckflächen*. Though the strike of these joints varies greatly, the dip is usually at an angle of 5° to 35° to the stretching. These joints are later in origin than the cross-

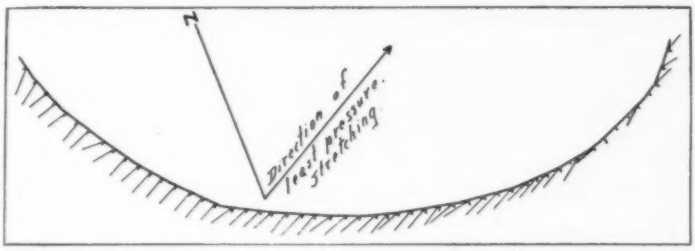

FIG. 3.—Diagrammatic sketch of slickensides on diagonal joints. The curved line is the strike of the joints, the short heavy lines are the direction of dip, and the long thin lines are the horizontal projection of the slickensides. Zobten granite. (After Cloos.)

joints since they commonly displace and offset the aplite and quartz dikes. They are, however, still very old, for reasons that will soon be apparent. If one considers a cross-section of the end of a granite mass, such as the front face of the block in Figure 2, it is to be noticed that the *Streckflächen* offset the cross-joints and their accompanying dikes, and that the relations of movement are everywhere those of normal faulting. According to the diagram, it is evident that the mass was elongated from side to side after the *Streckflächen* had formed, or else at the same time that the joints were forming, and that normal faulting along these surfaces accommodated the rigid mass to this extension. Further, when the slickensides on the *Streckflächen* were examined it was found that the horizontal projection of the direction of the striations was everywhere the same as the direction of the stretching. Cloos gathers from this that the tectonic force continued some time after the solidification of the magma, and in response to this stress, the *Streckflächen* formed, yielding by normal faulting so that the rigid mass could be further elongated in

the direction of the stretching. Figure 3 shows schematically this parallelism between the direction of least pressure—the stretching—and the horizontal projection of the slickensides in the granite near Zobten, Silesia. It is evident here that joints which strike and dip in many directions show movement in one and the same direction.

Pseudobatholiths.—Special attention to the variable pitch of the stretching and to variations in the dip of the foliation and the customarily flat-lying lager-joints has led the author to further interesting conclusions respecting the shape of the batholithic masses studied. In general these features within any particular massif exhibit an anticlinal or dome-like arrangement which is only very gentle in some cases though more pronounced in others. The block diagram in Figure 2 shows the arched nature of the stretching from right to left; if now the flow bands, schlieren, and *l*-joints from front to back were also arched, the conditions found in nature would be more closely reproduced. Cloos attributes this arching of primary features to the conflict of magmatic with tectonic forces, and believes that, in general, the root, or the underlying source of the magma, is to be found beneath the crest of the dome (the shield). In these discordant bodies, the tectonic force was not great enough to destroy completely the effects of magmatic movement, especially where this movement was most vigorous. In all probability this would be directly beneath the shield. From the deep-seated source, he considers the magma to have risen and spread in different directions, the amount and direction of horizontal spreading being determined largely by the faults, flexures, and lines of weakness in the surrounding wall-rock. The tectonic force might well impress its structural features, however, upon a magma which rises directly upward within the crust and which does not spread horizontally to any noticeable extent.

The best example of the dome structure of intrusive masses, and of the conclusions to be drawn from it, is the granite mass of Hauzenberg in the Bayrischer Wald. Here the elongate arch indicates that the roots are on the northeast side of the intrusive body. The contact and jointing at this place dip steeply northeast, whereas, farther to the southwest, the dip of the significant primary features becomes more and more gentle, until at the southwest edge of the present exposure of the granite it is almost horizontal. For more than a mile in the direction of dip at this place the nearly level floor can be seen, the intrusive granite resting directly on top. Figure 4 shows the probable form of this body along a northeast-southwest section. The Brocken granite in the Harz Mountains is appar-

ently another example of a huge tonguelike body or sill which exhibits a pronounced bend between the root and the end of the intrusion. The Riesengebirge and Lausitz massifs also are thought to have much the same sill-like structure with the source on the southwest, extending down deeply into the crust along the line of the Lausitz overthrust. The arching of the foliation, joints, and other primary structures culminates close to the southwest margins of these bodies giving a steep outward dip to the southwest of the crest and a long gentle northeast dip on the northeast side. In these cases it is probable that the northeast edges of the masses are shallow and sill-like, and will not be found to extend to very great depth. Present relations indicate that the granite masses of Striegau-Zobten and Strehlen-Friedeberg have risen along the important

FIG. 4.—Schematic profile through the "pseudobatholith" of the southern Bayrischer Wald. (After Cloos.)

structural break of the Sudetes between gneisses and schists. The Brocken granite and others likewise show the same genetic relationship to lines of structural weakness.

It seems to the reviewer that, applying the conception of rotational strain to the yielding of solidified granite bodies by normal faulting along diagonal joints, the conclusion may be reached that the plastic magma itself was elongated in a direction at approximately 45° to the direction of application of force, instead of at right angles to the force, as Cloos and his associates seem to take for granted. The direction of flow in the plastic granite, as evidenced by the stretching, and the direction of movement in the rigid rock, as shown by the horizontal projection of the slickensides, are identical. We cannot well think of rigid rock in the earth yielding continually at right angles to the direction of compression. Are we not, therefore, driven to believe that the plastic fluid, too, may have partially yielded in accordance with the principles of rotational strain?

FRANK A. MELTON

The Geology of New Hampshire. By JAMES W. GOLDTHWAIT. New Hampshire Academy of Science Handbook No. 1. Concord: Rumford Press, 1925. Pp. 86; 22 figs.; 27 plates. $2.00.

Hitchcock's monumental *Geology of New Hampshire* appeared almost fifty years ago and has long been out of print. Since then no attempt had been made to present the story of the development of the rock structures and surface features of New Hampshire until Goldthwait commenced the preparation of the present volume. During these fifty years many new facts have become known and interpretations have advanced correspondingly.

Goldthwait's purpose has been, apparently, to present the subject matter in simple, direct form so as to be serviceable both to the geologist and to the serious-minded citizen or summer visitor as well. In this he has been successful. So far as practicable, maps, pictures, and diagrams tell the story, and the text avoids detail.

Such a diversified subject cannot appeal equally at all points to any reader; hence the chapters are short and somewhat independent in content. Only four pages are allotted to the bed-rock geology "because relatively few people find it interesting and because a fuller treatment would demand long-continued and specialized field work, of which there is no immediate prospect." Many geologists will doubtless be disappointed by this meager discussion of the hard-rock geology of this long-settled state. Three pages of text and two of figures are given to the carving of the upland, and all the rest of the book is devoted to the Quaternary. The glacial geology and post-glacial changes are admirably presented, and therein lies the chief value of the volume. Good illustrations make the book very attractive.

R. T. C.

The Earth and the Stars. By C. G. ABBOT. New York: D. Van Nostrand Co., 1925. Pp. xii+264.

One seldom finds, among American men of science, a specialist of the prominence of Dr. Abbot who will attempt to scan the major field of his special interest for the benefit of his fellow-men. The "humanizing of knowledge" has been urged by several agencies. But in the highly specialized fields of the sciences the results have been quite insignificant. Abbot's *The Earth and the Stars* is a premeditated attempt to present to the interested, intelligent, but non-technical reader the whole field of modern

astronomy with its intricate problems and brilliant achievements. It therefore merits commendation.

The title leads one to expect a more extended discussion of the earth, but the treatment is thoroughly astronomical: the earth is considered mainly as a point of view. Aside from the casual mention of the age of the earth in the chapter on the sun, the use of the cast of a fossil footprint as analogous to a dark line in a reverse spectrum, and a few similar occasional references, there is devoted a chapter of twenty-four pages to the earth and the moon. In this chapter about four pages are devoted to size, shape, weight, and internal structure of the earth. The remainder of the chapter has to do with the conditions governing life on the earth, measurements of the velocity of light, the earth's atmosphere, the seasons, the tides, and the moon.

Two conspicuous attempts have been made to popularize the book: first, by inserting at the close of the first chapter the question regarding the existence of "thoughtful life" on other celestial bodies as the "great enigma of astronomy"; second, by enlarging on incidents of popular interest. The first may be pardoned, for, like a good astronomer, the author forgets the "great enigma" save for a casual reference or two in the remainder of the book. The second method of stimulating popular interest occasionally overshadows the text. For instance, more pages are devoted to the description of Locke's "Moon Hoax" of 1835 than to the description of the moon itself.

One conspicuous omission will force itself upon most geologists, namely, the absence of any adequate reference to the origin of the solar system and the earth. Laplace is dismissed with a page-length discussion of Jean's tidal theory in the chapter "Building the Universe." The earlier American application of the tidal disruption principle is not mentioned.

However, for the reader who has a background of chemistry and physics the book will prove most interesting and valuable. Students of those fields, and of geology, may turn to it to find carefully generalized statements of the results of the recent researches in astronomy and astrophysics. Shapley, Russell, Van Rhijn, Eddington, Campbell, among many others, are met in easy, informal terms. Especially helpful is the way in which these results are correlated and their significance emphasized in their relationship as steps in the solution of the larger problems.

The volume is one of a series in modern sciences by the publishers. To the reviewer the form is not particularly pleasing. Here and there the illustrative material is not well cared for; some of the diagrams are poorly

drawn and not given adequate explanation. But on the whole the informal style of the author and the simplicity with which he achieves difficult explanations will make the book thoroughly acceptable to the intelligent layman.

A. C. SWINNERTON

Unusual Forms of Fossil Crinoids. By FRANK SPRINGER. *Proceedings United States National Museum* (1926), Vol. LXVII, Art. 9, pp. 1–137; plates, 1–26.

In the course of his extensive research among the Paleozoic crinoids, Dr. Frank Springer has accumulated a vast amount of unpublished information concerning many genera. In the present paper he presents the results of his observations upon certain species of a number of peculiar genera of the Fistulate Inadunata. The peculiar crinoidal features which are discussed are as follows:

1. The coiled bilateral stem, manifest in the genera *Myelodactylus*, *Ammonicrinus* n. gen., and *Camptocrinus*.

2. The recumbent arms exhibited in *Macrostylocrinus*, *Gilbertsocrinus*, *Platycrinus*, *Dichocrinus*, and *Acrocrinus*.

3. Additional elements in the calyx of *Acrocrinus*.

4. The winglike radial processes present in *Pterotocrinus*.

5. Heterotomous branching of the arms in *Paradichocrinus* n. gen.

6. Unequal radials in *Agassizocrinus*.

7. The inflated ventral sack present in certain genera of the Poteriocrininae, *Pachylocrinus*, *Abratocrinus*, *Culmicrinus*, *Aulocrinus*, *Ulrichicrinus* n. gen., *Woodocrinus*, *Zeacrinus*, *Coeliocrinus*, *Hydreionocrinus*, *Decadocrinus*, *Scytalocrinus*, and *Timorocrinus*.

8. The last section of the paper is devoted to a brief discussion of the most remarkable crinoid fauna from the Permian beds of Timor, which has been described by Professor Johannes Wanner.

Altogether about sixty different species are more or less fully discussed, fifteen of which are described for the first time. Three new genera are also named and defined.

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